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Control Strategies for In-Use Vehicles

Environmental Protection Agency

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CONTROL STRATEGIES FOR IN-USE VEHICLES

U. S. Environmental Protection Agency
Office of Air and Water Programs
Mobile Source Pollution Control Program
Washington, D.C. 20460
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A number of alternatives are potentially available to the states to control emissions from in-use vehicles. The document deals with the "hardware" approaches to the following alternatives for emission control: (1) programs of periodic inspection and maintenance of vehicles to minimize excessive emissions that result from inadequate or improper vehicle maintenance; (2) the retrofitting of emission control systems to vehicles not originally so equipped, or the installation of more effective control systems on already-controlled vehicles; and (3) the conversion of motor vehicles to permit their operation using gaseous fuels. The major results are presented of the feasibility, emission reduction effectiveness, and costs of the various hardware approaches to in-use vehicle emission control.

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This report sets forth the findings and conclusions of work sponsored by the Environmental Protection Agency, or available to the EPA from other sources, on the technological feasibility, effectiveness, and costs of reducing the emission of air pollutants from automobiles currently in use. Some of the work on which this report is based was initiated as far back as 1969, while some other work was initiated later and was completed only in the last few months.

While many individuals participated in and deserve credit for various aspects of designing and carrying out the experimental work on which this report is based, the data that was generated from the individual projects was translated into the format of this report by Mr. Joseph Merenda, Assistant to the Director, Mobile Source Pollution Control Program, EPA; and by Mr. Steven Kuhrtz, who worked as a Staff Assistant in that office as a part of his graduate training program at Dartmouth College, Hanover, New Hampshire.

Additional copies of this report are available from the Mobile Source Pollution Control Program, Office of Air and Water Programs, Environmental Protection Agency, Washington, D.C. 20460.

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Chapter 1 OVERVIEW

1.1 INTRODUCTION

BACKGROUND

The Clean Air Act[1] provides two basic strategies for controlling air pollutant emissions from motor vehicles. The United States Environmental Protection Agency is empowered to promulgate and enforce emission standards applicable to new motor vehicles; this has been done on an increasingly stringent basis since the 1968 model year. The States are responsible for the establishment and enforcement of emission control strategies which apply to vehicles in use, to the extent that limitations on vehicular emissions beyond those resulting from the Federal new vehicle standards are necessary to allow each State to achieve and maintain the National Ambient Air Quality Standards.

In preparing their implementation plans for achievement of the air quality standards, a substantial number of States have determined that the application of control strategies to in-use vehicles will be necessary if the objectives to the Clean Air Act are to be fully achieved. A number of alternatives are potentially available to the States to control emissions from in-use vehicles. These include programs of periodic inspection and maintenance of vehicles to minimize excessive emissions that result from inadequate or improper vehicle maintenance; the retrofitting of emission control systems to vehicles not originally so equipped, or the installation of more effective emission control systems on already-controlled vehicles; the conversion of motor vehicles to permit their operation using gaseous fuels; restrictions on the use and parking of vehicles and modification of traffic flow patterns; improvements and expansion of public transportation systems together with incentives or restrictions to ensure the more extensive use of those systems in place of private vehicles; modification of social patterns which influence transportation patterns, such as work schedules; and restrictions on land use to influence transportation needs and patterns.

The first three approaches have in common their dependency on the application of emission control limitations to individual vehicles without necessarily altering the mode or frequency of use of those vehicles; these may be referred to as "hardware" approaches. In contrast, the other approaches seek to modify vehicle useage patterns without altering the emission characteristics of the individual vehicles and can be seen to be complimentary to the "hardware" approaches.

SCOPE

This document deals with the "hardware" approaches to in-use vehicle emission control described above; namely, inspection/maintenance programs, retrofit programs, and conversion of vehicles to permit the use of gaseous fuels. The "non-hardware" approaches are discussed in other EPA reports.[2,3] This document presents the major results of recent studies and evaluations made by the Environmental Protection Agency of the feasibility, emission reduction effectiveness, and costs of the various "hardware" approaches to in-use vehicle emission control.

In general, the emphasis of this document is on providing basic emission reduction and cost data which may be useful to the States in evaluating the alternative approaches to in-use vehicle emission control, as those approaches may be applied to their particular air quality requirements. No attempt has been made to identify a "best"in-use vehicle emission control approach or an optimum combination of approaches. Such evaluations must be performed on a region-by-region basis, taking account of the time period over which emission reductions must be achieved and the magnitudes of the needed reductions, and using vehicle population data representative of the area under consideration.

ORGANIZATION

This document is organized into four chapters. Chapters 2, 3, and 4 deal, respectively, with inspection/maintenance programs, retrofit approaches, and gaseous fuel conversion. Each of those chapters provides a detailed discussion of the data and conclusions relating to that aspect of in-use vehicle emission control. This chapter presents an overview of the subject by presenting the major findings with respect to each approach.

1.2 SUMMARY OF MAJOR FINDINGS

1.2.1 INSPECTION/MAINTENANCE

Inspection/maintenance programs aim at reducing emissions from in-use vehicles through ensuring that the emission levels of those vehicles are not permitted to deteriorate,through inadequate or improper maintenance, substantially beyond the levels of which the vehicles were capable when new. Inspection/maintenance programs can accomplish emission reductions only to the extent that voluntary maintenance is inadequate in maintaining the vehicles in good condition.

Studies conducted using representatives samples of privately-owned in-use automobiles have demonstrated that significant reductions in the aggregate emissions of those groups of vehicles can be obtained through additional maintenance. It has been found that approximately 50% of the vehicles in a typical sample had malfunctions or maladjustments which, when corrected, resulted in a decrease in emissions. When maintenance was performed on those vehicles, the average point-in-time reductions in emissions for the entire sample (including the vehicles not maintained) ranged up to 25% for exhaust hydrocarbons (HC) and up to 19% for carbon monoxide (CO). No statistically significant changes in the average emissions of oxides of nitrogen (NOx) were found. These studies lead to the conclusion that current voluntary maintenance practices are inadequate to keep the entire in-use vehicle population at the minimum levels of emissions of which it is capable; and, therefore, that implementation of a required inspection/maintenance strategy could result in significant reductions in HC and CO emissions.

The actual emission reductions that can be achieved over time through an inspection/maintenance program will depend upon the rate and extent of emission control deterioration between the required inspection/maintenance events. A study of this factor is being conducted,but sufficient data are not yet available to define the influence of deterioration on the average reductions achievable by an inspection/maintenance program over time. However, based on an analysis of the frequency and distribution of current voluntary maintenance of emission-related components, a preliminary estimate of the average effectiveness over time has been made. It has been estimated that inspection/maintenance on an annual basis may be expected to achieve emission reductions of up to 12% in light duty vehicle exhaust HC emissions and up to 10% in light duty vehicle CO emissions. More frequent inspection/maintenance could achieve larger reductions.

The emission reduction effectiveness of several alternative approaches to inspection/maintenance has been evaluated. These include: emission testing at idle only, emission testing using a loaded test cycle, engine parameter diagnosis, and mandatory maintenance of specific emission-related components or adjustments. While the mean reductions that were observed for the emission testing approaches were the largest, the empirical data currently do not permit differences in the effectiveness of the various types of approaches to be distinguished at a 90% confidence level.

This is not to say, however, that all of these approaches show equal promise for effective application in inspection/maintenance programs for the general population of in-use light duty vehicles. Engine parameter diagnosis and mandatory maintenance approaches must be designed to correspond to the specific emission control systems employed on each type of vehicle to be inspected. Thus, a specific form of one of these approaches may not be broadly applicable to the entire population of in-use light duty vehicles; particularly, to those produced in future model years.

Emission inspection approaches, on the other hand, can be considered more generally applicable, to the extent that the emission measurements made in the inspection test accurately reflect the vehicles' emissions during typical urban driving. The relatively poor correlation for current vehicles between idle emission measurements and emission rates resulting from typical urban operation indicates that vehicles may be adjusted so as to satisfy idle emission inspection standards without achieving reductions in true mass emissions. Loaded emission tests provide a significantly better measure of the emission levels which the vehicle would produce in typical driving, although all short emission tests are hampered by their inability to assess emissions from a cold start. In general, it appears that, among the inspection/maintenance approaches which are generally applicable to the current in-use light duty vehicle population, emission testing using a loaded test cycle has the greatest likelihood of achieving maximum emission reductions in practice. This conclusion is not, however, intended to rule out the possibility that other inspection/maintenance approaches of comparable effectiveness may be designed for specific segments of the in-use vehicle population.

Estimates of the cost of vehicle inspection and of the additional maintenance required through an inspection/maintenance program have been made. It has been estimated that emission testing using a loaded test cycle in State-operated inspection lanes would cost approximately $2 per vehicle. Extensive engine parameter diagnosis has been estimated to cost approximately $8 per vehicle. It has been estimated that the cost of the additional maintenance required by an annual inspection/maintenance program in which 30% of the vehicles failed inspection would cost an average of about $2 per vehicle in the population. Of course, the cost per vehicle failing the inspection would be higher and would vary significantly among failing vehicles, depending upon the nature of the malfunction.

The above conclusions regarding inspection/maintenance approaches apply specifically to the types of vehicles that are currently a part of the in-use vehicle population. It is not possible at this time to define the effectiveness which inspection/maintenance programs may achieve if applied to future model year vehicles using substantially different types of emission control systems.

1.2.2 RETROFIT

Retrofit approaches go beyond the attempt made by inspection/maintenance approaches to keep in-use vehicles at minimum levels consistent with their original design. In a retrofit approach, the goal is to reduce an in-use vehicle's emissions below its "well-maintained" levels, through adding new emission control devices or through modifying the original design to achieve lower emissions.

Evaluation of available retrofit devices has indicated that retrofit systems exist which can achieve substantial reductions in emissions of HC, CO, and NOx from light vehicles that were not originally subject to Federal emission standards (pre-controlled vehicles). Maximum concurrent reductions of approximately 70% in exhaust HC, 65% in CO, and 50% in NOx, relative to the vehicle's emissions when in a properly maintained condition, have been observed. Although concurrent reductions of these magnitudes can be obtained only with relatively expensive devices, similar reductions in CO and NOx are achievable individually using much less costly retrofit approaches. Devices are also available which achieve lesser reductions in all three pollutants at lower cost.

Application of retrofit approaches to pre-controlled light duty vehicles can achieve emission reductions of up to the magnitudes stated above without major compromise in vehicle performance that would render the vehicles unsafe. Effects of retrofit devices on fuel economy appear to vary markedly among different approaches but have not been extensively evaluated. The installed cost of various retrofit approaches ranges from about $20 to as much as $175.

Limited durability testing of light duty vehicles equipped with various retrofit approaches has led to the conclusion that actual achievement and maintenance of emission reductions similar to those stated above can be ensured only if retrofitted vehicles are maintained in good condition; emission-related components and adjustments that are not themselves a part of the retrofit system must be maintained as well as the retrofit. Thus, periodic inspection and maintenance of retrofitted vehicles appears to be a necessary part of any retrofit strategy.

Retrofit approaches are also potentially applicable to light duty vehicles already equipped with emission control systems if different or more effective systems are added. Empirical data quantifying the emission reductions achievable through retrofitting such vehicles are very limited; however, based upon the effectiveness of retrofit approaches when applied to pre-controlled light duty vehicles, it appears reasonable that emission reductions of up to

50% in exhaust HC and CO per vehicle could be achieved through retrofitting 1968 through 1974 models. It is expected that such reductions could be achieved only through the use of relatively costly ($80 to $160 per vehicle, on average) devices requiring the use of unleaded gasoline. Reductions of up to 40% in NOx per vehicle could probably be achieved through retrofitting 1968 through 1972 models using devices in the $30 to $50 price range. Applicability of such approaches to various model years in California would differ because of different new vehicle emission requirements there.

The emission reductions cited above as feasible through retrofitting light duty vehicles refer to the reduction per vehicle. Since retrofit approaches apply, in general, only to a portion of the in-use vehicle population, the overall emission reductions achieved by retrofit programs would be substantially less than those figures. Calculation of the overall effectiveness of retrofit programs must be performed on a region-by-region basis since significant differences in vehicle population statistics exist. However, based upon nationwide average vehicle population data, it can be concluded that exhaust emission retrofit programs for pre-controlled and controlled light duty vehicles could be expected to achieve significant impacts on total light duty vehicle emissions throughout the 1975 to 1980 time period.

1.2.3 GASEOUS FUEL CONVERSION

Conversion of motor vehicles to permit their operation using gaseous fuels can be considered a special case of retrofit, but implementation of such an approach to in-use vehicle emission control involves a number of considerations beyond those required in evaluating retrofit approaches which simply change the engine design. Those additional considerations include the availability of adequate supplies of the gaseous fuel, the availability of, or feasibility of constructing, an adequate number of fueling facilities for the converted vehicles, and the possible impact on emissions from stationary sources of diverting gaseous fuel supplies to vehicular use. Based upon such considerations, it has generally been concluded that conversion of large numbers of privately-owned vehicles for gaseous fuel operation is not feasible, and that gaseous fuel conversion strategies are feasible only for fleet-operated vehicles.

In spite of the large numbers of vehicles which have been converted to use gaseous fuels, data on the emission reductions attainable through such conversions are relatively limited. Available data indicate that substantial reductions in emissions of HC, CO, and NOx can be achieved through gaseous fuel conversion, although in a number of cases gaseous fuel conversion had actually increased emission levels. Data indicate that when 1970 model year and earlier light duty vehicles are converted for operation on gaseous fuel, and ignition timing and air/fuel ratio are optimized for low emissions, reductions of up to 80% in HC and CO and up to 60% in NOx are achievable per vehicle.

The initial cost of gaseous fuel conversion is substantial. Costs for converting a single vehicle to gaseous fuel operation are estimated in the range of $450 to $800 or more, depending on the type of fuel and the vehicle range between fueling stops desired. This cost is exclusive of any cost necessary to provide fueling facilities. On the other hand, decreased operating and maintenance costs when using gaseous fuels have motivated a large number of the conversions made to date, although the extent of such savings may vary widely.

As with other retrofit strategies, the overall effectiveness of a gaseous fuel conversion strategy must be evaluated on a region-by-region basis.

Beyond the differences in vehicle population data among regions and the different magnitudes of emission reductions required, the availability of fuels and impact of fuel switching is particularly regional in nature. Therefore, no general conclusion can be drawn regarding the feasibility and desirability of gaseous fuel conversion as an in-use vehicle emission control strategy. However, evaluation of such strategies in a few specific instances has indicated that unless fleet vehicles contribute a large portion of the total vehicular emissions in a region, and unless the fleet to be converted is relatively stable in the sense of not being rapidly replaced by new vehicles, emission reductions through gaseous fuel conversion of fleet vehicles cannot be expected to be large or long-lived.

REFERENCES - CHAPTER 1

1. Clean Air Act, 42 U.S.C. 1857 et seq., as amended by P.L. 91-604 December 31, 1970.
2. Evaluating Transportation Controls to Reduce Motor Vehicle Emissions in Major Metropolitan Areas: An Interim Report, Institute of Public Administration, Washington, D.C., March 16, 1972.
3. Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas (Six Cities Transportation Study), TRW Systems Group, McLean, Va., July, 1972.

Chapter 2 INSPECTION AND MAINTENANCE OF IN-USE VEHICLES

2.1 INTRODUCTION

The degradation of automotive emission control resulting from improper or insufficiently frequent maintenance suggests the possibility of achieving significant reductions of current levels of motor vehicle emissions through the periodic inspection and enforced maintenance of in-use vehicles. This chapter presents the currently available information concerning the feasibility of alternative test procedures for the periodic inspection of extensive populations, the potential effectiveness in reducing automotive emission levels through emission related maintenance procedures, and the potential cost burden attributable to the implementation of alternative approaches for the inspection/maintenance strategy.

2.1.1 TYPES OF INSPECTION/MAINTENANCE APPROACHES

All inspection/maintenance approachs include, conceptually, two phases: an inspection phase, used to screen the in-use vehicle population to determine which of those vehicles should be required to receive maintenance; and a maintenance phase, in which appropriate corrective maintenance is performed on the selected vehicles. Alternative inspection/maintenance approaches can be categorized according to the nature of their inspection phases as follows:

Emission Inspection Approaches - Each vehicle included in the program is subjected to an emission test and the results compared with a set of in-use vehicle emission standards. Vehicles with emissions in excess of the standards are considered to have failed, and are required to have maintenance performed. An emissions retest may be required after the maintenance to ensure that the failed vehicle has been brought into compliance with the emission standards.

Engine Parameter Inspection Approaches - Each vehicle included in the program is subjected to a sequence of diagnostic tests which seek to evaluate the mechanical condition of various emission-related vehicle systems and determine if malfunctions or maladjustments are present. Vehicles showing measurements outside of accepted tolerance ranges are considered to have failed,and are required to have corrective maintenance performed. This approach bypasses the question of each vehicle's emission levels, although in some cases emission measurements may be made to evaluate the state of certain vehicle systems (e.g., measurement of idle CO concentration to evaluate proper idle air/fuel ratio adjustment).

Mandatory Maintenance Approaches - Each vehicle, independent of its emission levels or mechanical condition, is required to have specific maintenance operations performed at required intervals. Thus, the inspection phase is simply eliminated; and the appropriate maintenance is explicitly specified for each type of vehicle and identical for all vehicles of that type, rather than being whatever maintenance is necessary to achieve compliance with an emission standard or to ensure that specific vehicle systems pass diagnostic checks.

The requirements for the identification of the optimal engine components to be tested in a functional, or diagnostic, inspection approach also exists for the identification of the components to be periodically replaced or adjusted in a mandatory maintenance program. Any mandatory adjustments must rely upon some measurement of functional performance to ensure the proper setting. If the adjustment is not made to the specifications of the maintenance policy, the regulations have not been properly executed. For these reasons, there are only subtle differences between the mandatory maintenance approach and an engine parameter inspection approach. These exist primarily within the enforcement implications rather than the technologies involved.

Three alternative configurations characterize the operational format of the inspection program. These alternatives are described below. In each case, it is anticipated that the private service garages and dealerships comprising the automotive repair industry will provide the requisite maintenance. Although the selection of a specific alternative configuration should not conceptually have an impact on the effectiveness of the strategy, each configuration may have substantial effects on the feasibility of providing effective enforcement, the total cost burden of the initial capital investment, or the inconvenience imposed upon the vehicle owner.

Operational Configurations for the Inspection Program

* Publicly Operated Lane System - The testing functions are provided directly by the appropriate state or municipal agency in a system of publicly owned and operated facilities designed exclusively for the testing of motor vehicles.

- Privately Operated Lane System - The testing is performed by a private organization under contract to the appropriate government agency in a system of inspection lanes designed exclusively for the testing of motor vehicles.
- Licensed Garage System - The testing is performed by existing private service or repair agencies within the maintenance industry. Each inspection facility is certified, licensed, and controlled by the appropriate government agency.

2.1.2 EVALUATION OF INSPECTION/MAINTENANCE APPROACHES

The optimal design of the inspection/maintenance strategy requires the assessment of numerous interacting factors which have a substantial impact upon the effectiveness and the incremental economic burden imposed by the implementation of such programs. Certain of these factors may be evaluated to provide an initial assessment of the feasibility and the relative performance characteristics of the various inspection/maintenance approaches, thereby screening the multitude of potential alternatives. Additional parameters must then be evaluated in order to assess the actual cost-effectiveness of each approach as a function of time.

The following factors are the major determinants of the potential feasibility, effectiveness, and cost-effectiveness of the inspection/maintenance strategy.

* The extent to which the lack of voluntary maintenance by the general public causes in-use vehicles to differ from the original manufacturer's specifications.

* The magnitude of the emission increases which result from such deviations from manufacturer's specifications.

* The effectiveness with which the inspection testing procedure can identify from among the entire vehicle population those vehicles with excessive emissions resulting from engine malfunctions and maladjustments.

* The information value of the inspection test results in identifying the specific maintenance actions required to restore the vehicle to a condition which is in compliance with the inspection standards.

* The effectiveness of the repair industry in applying proper maintenance to reduce emissions from those vehicles identified as having malfunctions or maladjustments.

* The rate and extent of the deterioration of emission control following maintenance.

* The correlation between the inspection test procedure and the Federal Certification Test Procedure as it relates to the impact of vehicular emissions upon ambient air quality.

* The initial capital investment and the annual operating costs of the inspection facilities and program administration.

* The maintenance costs and any indirect costs or savings such as changes in fuel economy or the substitution of required maintenance for existing voluntary maintenance schedules.

2.1.3 ORGANIZATION OF CHAPTER 2

The remainder of Chapter 2 is devoted to presenting the results of evaluations of the feasibility, effectiveness, and cost-effectiveness factors identified above. Section 2.2 provides an overview of the characteristic test procedures considered feasible for use in the inspection process. Section 2.3 presents an assessment of the feasibility and relative performance characteristics of three representative approaches for the inspection/maintenance strategy. The empirical results of three independent sample fleets are evaluated.

One factor which remains to be quanitified in a definitive manner is the rate and extent of emission control deterioration following maintenance. Studies are presently being conducted to provide an assessment of this parameter such that the true effectiveness of the inspection/maintenance strategy can be defined. However, until such information is developed, available data must be used to provide an estimate of the expected average effectiveness over time. Accordingly, an analysis is presented in Section 2.4 which sets forth a methodology for estimating the impact of the inspection/maintenance strategy utilizing existing empirical data.

Section 2.5 identifies the degree of correlation with the Federal Certification Test Procedure demonstrated by numerous alternative emission inspection procedures, and discusses the need for such correlation to ensure the continued effectiveness of inspection/maintenance programs.

Section 3.6 summarizes the results and presents the major conclusions concerning the existing state of technology and the potential impact of the inspection/maintenance strategy.

2.2 DESCRIPTION OF INSPECTION PROCEDURES

The inspection phase of an inspection/maintenance program is a screening procedure applied to the entire population of in-use vehicles subject to inspection/maintenance. Its function is to maximize the cost-effectiveness of the inspection/maintenance program by identifying for required maintenance only those vehicles likely to exhibit significant emission reductions if given additional maintenance. The inspection procedure may also serve to provide a check on the quality of the maintenance performed on the failed vehicles if they are required to be retested after maintenance.

The investigation of alternative procedures that satisfy the performance requirements of the inspection process leads to the identification of two general categories: direct emission measurement tests and engine parameter, or diagnostic, tests. A detailed description of the principal technical factors which must be considered when selecting a particular inspection procedure is presented in the following subsections.

2.2.1 EMISSION INSPECTION PROCEDURES

The feasibility and effectiveness of the emission inspection approach depends upon the availability of emission test procedures which can reliably identify vehicles whose emissions can be reduced through maintenance. First, let us briefly review the major characteristics of emission test procedures.

Typical urban driving patterns are composed of four basic types of operating modes: idle, acceleration, deceleration, and constant speed or cruise modes. The characteristic emission rates of current in-use vehicle types vary substantially among the various operating modes. Accordingly, the total emissions generated while a vehicle is operated over a driving cycle are sensitive to the extent of vehicle operation in the various modes during the driving cycle. In general, if the emission measurement is to provide a meaningful indication of the vehicle's emissions during typical urban driving, the driving cycle must accurately reflect urban driving patterns typical of the current vehicle population.

The measurement of vehicular emissions is also known to be affected by the methodology utilized for sampling and analysis of the emissions produced during vehicle testing, and by the pre-test vehicle conditioning procedures employed. Thus, the definition of an exhaust emission test must include a description of the vehicle pre-conditioning procedures, the driving cycle which prescribes the vehicle operation during the collection of the exhaust gas sample, the collection or sampling procedures, and the analytical techniques used to measure the amount of pollutants in the exhaust sample. Alternative methods which have been employed for each of these emission test procedure components are summarized in Table 2-1.

The Federal Certification Test Procedure[1] (FTP) is the standard method used to quantify light duty vehicle emissions. Although the FTP would provide the most reliable measure of excessive emissions from in-use light duty vehicles, it is far too costly and time consuming to be feasible for the periodic testing of large vehicle populations. Aside from the expense of the necessary equipment, the test pre-conditioning requires that the vehicle remain inoperative for at least twelve hours prior to initiating the emission test, and the driving cycle, derived from data obtained through operating instrumented vehicles over a typical urban route, is 23 minutes in length. Therefore, it is necessary to consider

TABLE 2-1

OPERATIONAL COMPONENTS OF EMISSION TEST PROCEDURES

VEHICLE PRE-CONDITIONING	VEHICLE OPERATING CYCLE	SAMPLING METHODOLGY	ANALYTICAL METHODOLOGY
1. Cold Start (test is initiated with cold engine)	1. Idle Mode	1. Exhaust Stream Probe	1. NDIR Analysis: Measurement of CO, NO, and HC measured as n-Hexane.
2. Hot Start (engine temperature is stabilized prior to initiating test)	2. Dynamic Modes a. Steady State Modes b. Transient Modes	2. Constant Volume Sampling	2. FID Analysis: Measurement total hydrocarbons.
			3. NDIR/NDUV Analysis: Measurement of NOx as NO + NO_2.
			4. Chemiluminescent Analysis: Measurement of total NOx as NO.

whether alternative test procedures are available which would be feasible for in-use vehicle emission inspection testing.

VEHICLE PRE-CONDITIONING

There are two basic alternatives for vehicle pre-conditioning: cold start and hot start testing. In cold start testing, the vehicle is allowed to stand unoperated for an extended period (typically twelve hours or more) at a specified ambient temperature to allow all of the vehicle systems to attain an ambient temperature. Then the vehicle testing is initiated with the cold vehicle and emissions are normally measured from the beginning of the vehicle start up procedure. Cold start pre-conditioning simulates the emissions from a vehicle being started after a period of extended shutdown, as, for example, when first started after overnight parking. Cold start testing allows evaluation of systems (such as choke) which do not function when the vehicle has attained normal operating temperatures; and, therefore, is considered the best type of test to employ for extensive evaluation of vehicle emissions. However, the extended time required for pre-conditioning makes a cold start test unfeasible for in-use vehicle emission inspection.

The hot start test is conducted with the vehicle starting from a temperature at or near normal operating temperature. One version, the hot-restart test employed in the 1975 Federal Test Procedure,[1] requires restarting the vehicle after a ten-minute soak period at ambient temperature following vehicle operation. For this test, emissions are measured from the beginning of the vehicle restart procedure. Another type of hot start test which is often considered for in-use vehicle emission inspection testing does not measure emissions from the beginning of the vehicle start up procedure, but requires operation of the vehicle for a sufficient period to stabilize operating temperatures and then measures emissions from the stabilized, operating vehicle.

VEHICLE OPERATING CYCLES

Vehicle operating cycles (driving cycles) are characterized according to the types of driving modes which are simulated during the test. Of interest are the idle mode test cycle, cruise mode test cycles, and transient mode test cycles; the latter two may be classified as dynamic mode cycles.

The measurement of emissions only during the idle mode requires the least time and equipment, and is the most convenient operating mode for an emission measurement. The pollutant levels within the exhaust gas are measured during normal idle operation of the vehicle. There is no external power loading imposed on the engine. The idle procedure must specify whether the emission measurement is to be made with the transmission in "drive" or in "neutral" when testing vehicles with an automatic transmission. An idle mode test typically requires about two minutes to complete.

The operational requirements for emission measurements during dynamic mode driving cycles are substantially more sophisticated. A chassis dynamometer is required to simulate the loading which is imposed on the engine during actual driving conditions. The alternatives within this category may be composed only of cruise modes, or they may include the transient (acceleration and deceleration) operating modes.

The Clayton Key Mode[2] procedure is a typical cruise mode test cycle. The vehicle is positioned on the dynamometer and the driver accelerates until an indicated speed of 44 to 50 mph is attained; a steady cruise is maintained while the emission measurement is taken. The driver then decelerates to a cruise speed of 22 to 30 mph and the emission measurement is repeated. The final measurement is recorded while the vehicle is idling. The dynamometer provides a power absorption which simulates the loading due to the various sources of fluid and mechanical friction present during constant speed operation of the vehicle on the road. The power absorption used for the Key Mode Test is proportional to the third power of the road speed, providing a 30 horsepower load at 50 mph. Cruise mode tests typically require about three minutes to complete.

The inclusion of acceleration and deceleration in transient mode cycles provides a driving pattern which is clearly more representative of actual vehicle operation. It must, therefore, be expected that the associated emission measurements provide the best measure of vehicle emissions on the road. A transient mode test cycle requires additional loading capabilities to simulate the inertial effect of the vehicle mass. The requisite dynamometer and related equipment are substantially more sophisticated and costly than those required for a cruise mode cycle.

A transient mode driving pattern frequently used for emission testing is the Seven Mode Cycle.[3] The speed-time trace is shown in Figure 2-1. The vehicle is positioned on the dynamometer and driven over the prescribed test cycle. The dynamometer must be calibrated to apply a road load effect and an intertial load effect which are proportional to the weight of the vehicle. The exhaust emissions may be measured for the entire operating cycle or limited to specific segments of each individual mode. About five minutes is typically required to complete a transient mode test using the Seven Mode Cycle.

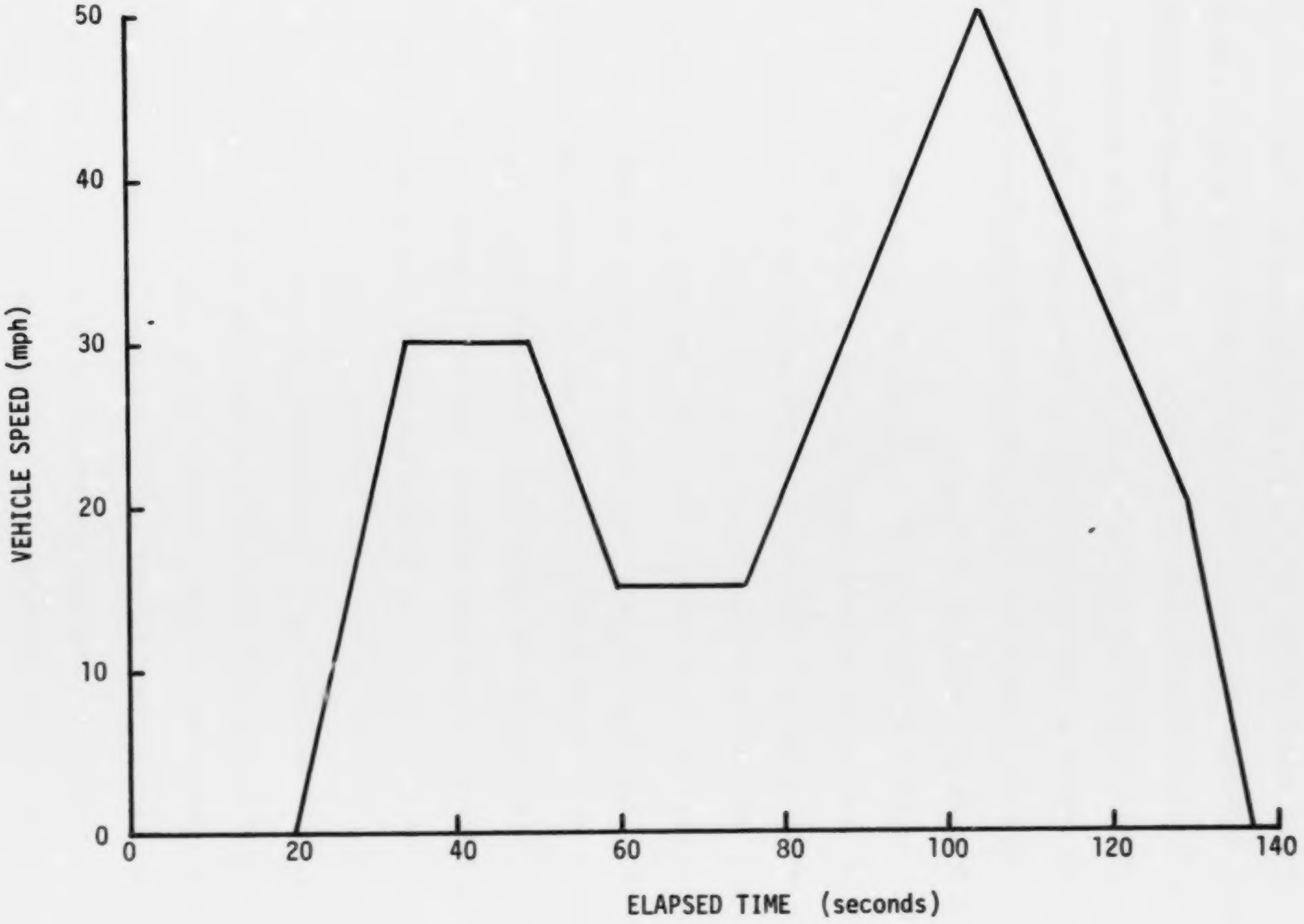

FIGURE 2-1

SEVEN MODE DRIVING CYCLE

SAMPLING METHODOLOGY

The techniques used to collect the exhaust gas sample for analysis have a direct impact on the emission measurement results. The least expensive technique for sampling the exhaust gas utilizes a collection probe which is inserted directly into the tailpipe. A slight vacuum is applied to the sample line and the exhaust gas is transferred to the analytical system for continuous analysis during the sampling period. The resulting analysis provides a measure of the concentration of pollutants within the exhaust mixture as a function of time.

An evaluation of the impact of automotive pollution requires a measure of the mass emission rate as a function of vehicle usage. The concentration measurement obtained using the probe sampling technique provides no indication of the mass of pollutants emitted without a concurrent measure of the exhaust flow rate. Analysis of vehicle exhaust volumes has shown that the mass flow rate over a given driving cycle is primarily a function of the vehicle weight and the measured concentration of the pollutant within the exhaust gas. This method provides an acceptable measure of the mean emission rate for large samples of vehicles; however, substantial error often results when calculating the mass emission rate for an individual vehicle.

A recently developed sampling technique[1] is used to directly determine the mass of pollutants being emitted from an individual test cycle. The procedure utilizes a Constant Volume Sampling (CVS) system which eliminates the need for the empirical conversion formula. The CVS technique provides an integrated measure of the total exhaust flow over the test cycle, and the sample which is analyzed provides an integrated measure of the average pollutant concentration during the entire cycle.

The mass emission rate as a function of vehicle usage (grams per mile) is then directly calculated.

Either sampling approach can potentially be used with any of the specific test cycles discussed previously.

ANALYTICAL METHODOLOGY

Three primary components of automotive exhaust are currently regulated. These are: unburned hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). However, the composite exhaust from the automobile engine is a complex mixture of many different gaseous (and particulate) reaction products of the combustion process. Accordingly, the emission measurement must be based upon analytical methodology highly specific for each component of concern and essentially insensitive to the presence of other components within the exhaust mixture.

Each specific test procedure may have unique constraints for the performance characteristics of the analytical system. In general, however, the time required to analyze the sample should be minimized. The total labor time required for an emission measurement is often the most significant cost element, due to the high skill level necessary for the personnel involved in the testing procedure. In addition, an excessive delay time between the collection of the sample from the exhaust stream and the completion of the analysis may confound the emission measurement due to the potential reactivity of the many gaseous components.

An obvious attribute desirable for any testing system is operational simplicity; thus, minimizing the probability of erratic measurement error.

The broad range of analytical technology potentially applicable to exhaust emission testing is beyond the scope of this report. The following text provides a brief description of the basic instrumentation currently used to fulfill the analytical requirements of motor vehicle emission test procedures.

Nondispersive Infrared Analysis - the operational principle of the nondispersive infrared (NDIR) analyzer relies upon the infrared energy absorption characteristics exhibited by certain molecular species. The attenuation of an infrared light source passing through a gaseous mixture is proportional to the concentration of the absorbing species within the mixture.

NDIR analysis is appropriate for any molecular species exhibiting a strong characteristic absorption peak within a narrow frequency band. The absorption peak must provide adequate resoltuion to avoid any interference resulting from the presence of other exhaust components which absorb at a similar frequency in the infrared.

NDIR analysis is typically used for the measurement of carbon monoxide and nitric oxide (NO). The water content of the exhaust sample generates interference within the absorption band of CO. This is generally overcome by passing the sample stream through a drying agent prior to entering the analyzer.

Exhaust gas contains a large number of unique hydrocarbon species. Many of the hydrocarbon molecules with complex bonding structures cannot be detected using NDIR analysis. A number of simple hydrocarbons, known as paraffins, exhibit strong infrared absorption peaks. Current motor vehicle exhaust compositions exhibit a reasonably constant proportionality between the paraffin content and the total hydrocarbon content. The NDIR instrument is sensitized for n-Hexane and a measure of the paraffin content is obtained which can then be related to total hydrocarbons using the proportionality constant.

Nondispersive Ultraviolet Analysis - in principle, the NDUV analyzer relies upon the same optical absorption phenomenon discussed above. The molecular species which can be analyzed using this approach exhibit characteristic absorption peaks within the ultraviolet frequency range.

The utility of NDUV analysis for exhaust emission testing is limited to the measurement of nitrogen dioxide (NO_2). The production of NO_2 occurs as the exhaust gas effluent cools, favoring the reduction of any residual oxygen by nitric oxide formed during combustion. A composite NDIR/NDUV system provides a useful measure of the total oxides of nitrogen (NO and NO_2) composition of the exhaust.

Analysis by Flame Ionization Detector - Flame ionization detectors provide a direct measure of total hydrocarbons. The sample is passed through a hydrogen flame ionizer which dissociates the hydrocarbon molecules, creating an ionized gas of charged carbon atoms. An electro-potential measurement across the gas is proportional to the concentration of carbon ions present. The measurement is directly related to total hydrocarbon content of the initial gas mixture. FID analysis is not affected by the presence of CO, CO_2, NO_x, or water. However, the procedure is extremely sensitive to the precise control of the sample flow rate through the analyzer.

Chemiluminescent Analysis - The reaction of nitric oxide (NO) and ozone produces chemiluminescent radiation (emission of energy in the red and infrared frequency range) which is proportional to the initial concentration of NO in the reaction mixture. Preceding the actual analysis, the exhaust gas sample is passed through a thermal converter to ensure the rapid conversion of any NO_2, which may be present, to nitric oxide. Injection of ozone into the sample stream initiates the reaction. The analyzer is calibrated to relate the intensity of the chemiluminescence to the initial concentration of nitric oxide.

SUMMARY OF EMISSION TEST PROCEDURES

Although a large number of alternative emission test procedures are possible through combinations of the components shown in Table 2-1, not all of these combinations would be practical. For example, selection of a simple driving cycle, such as a single idle mode, limits the practical choices of sampling and analytical methodology since the limited information content of an idle mode emission measurement would not justify the use of highly precise and accurate sampling and analytical techniques.

Table 2-2 outlines three alternative test procedures that are currently considered applicable for State inspection programs. These specific alternatives are representative of the range of costs and accuracy which can be expected for the present state of emission testing technology, and the existing vehicle population.

The present population, with the exception of post-1970 model year vehicles sold in California, has not been designed to comply with standards for NO_x emissions. Therefore, analytical requirements for NOx are not included among the alternatives shown in Table 2-2. Future vehicles (1973 and later model years) may necessitate the inclusion of NO_x measurement capabilities.

T A B L E 2-2

TEST PROCEDURE REQUIREMENTS

TEST TYPE	PERSONNEL	TEST TIME	EQUIPMENT REQUIREMENTS* for Exhaust Gas Concentration Measurements
No-Load Test Cycle			
Idle Mode	2	2 minutes	NDIR HC and CO Analyzer
Dynamic Test Cycles			
Cruise Mode	2	3 minutes	NDIR HC/CO Analyzer Chasis Dynamometer (Road Load Capabilities)
Transient Mode	2	5 minutes	NDIR Analyzers: CO_2, CO, HC (dual range) Chasis Dynamometer (Inertial Load Capabilities) Data Processing Systems: Analog to digital converter, computer, printout device.

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* Minimum requirements for manual operations.

Semi-automated procedures for high vehicle throughput would require data processing systems similar to those shown for the Transient Mode Cycle.

Mass emission measurements necessitate additional equipment for constant volume sampling capabilities. An additional 2-3 minutes per vehicle is required for the analytical procedures. There are additional personnel or instrument requirements.

2.2.2 ENGINE PARAMETER INSPECTION PRECEDURES

The second major classification of alternatives for the inspection process is the engine parameter approach. Parameter inspection provides a functional evaluation of selected engine components and adjustments.

Both the effectiveness and the cost-effectiveness of this approach are highly sensitive to the selection of the optimal parameters to be evaluated during each periodic inspection. The selection criteria for these engine parameters must reflect the extent and frequency of various types of malfunctions (or rates of maladjustment) and their impact on exhaust emissions.

Table 2-3 outlines the characteristics of an extensive engine parameter inspection. Three basic engine subsystems are identified for evaluation; and within each subsystem, there are identified individual engine components or adjustments which are important in the control of exhaust emissions.

TABLE 2-3

ENGINE PARAMETER INSPECTION*

Subsystem	Engine Parameter	Equipment Requirements	Inspection Time (Man hours)
Idle Adjustments	% Idle CO RPM, Timing	NDIR CO Analyzer Tachometer, Timing Light	0.15
Secondary Ignition	Plugs, Wires, Distributor	Electronic Engine Analyzer	0.25
Induction	Air Cleaner PCV Valve Air Injection System	Air Cleaner Tester Pressure Gauge Air Flowmeter	0.25

* The alternatives shown here were identified in the APRAC/CAPE - 13 study **(see Reference 5).**

The individual inspection parameters shown in this table are only appropriate for the present vehicle population, and its associated emission control systems. It cannot be assumed that these specific procedures are either necessary or sufficient for future model year vehicles with advanced emission control systems. As new vehicles enter the population, parameter inspection procedures must be re-evaluated to ensure that the program remains effective and cost-effective.

The failure limits for each inspection parameter are generally functional criteria which reflect the manufacturer's specifications. For the most part, this approach does not rely on the direct measurement of exhaust emissions. The only exception being the measurement of the idle mode volumetric concentration of carbon monoxide. Within the context of the engine paramenter inspection, % idle CO is considered a functional evaluation of the idle air/fuel ratio.

Although the procedures outlined in Table 2-3 would provide the most thorough inspection of a vehicle's state of maintenance, it would not necessarily provide the most cost-effective approach from the standpoint of reducing vehicle exhaust emissions. Certain of these engine parameters may malfunction infrequently and cause only a marginal increase of the exhaust emission levels. The incremental cost required to inspect such a component may be disproportionate with respect to the resultant impact upon the emission levels of the total vehicle population.

There are no operational constraints which restrict the specific combination of parameters selected for an inspection program. Logically, consideration should first be concentrated on those parameters which are most accessible, easily tested, and easily adjusted and which have the largest impact on emissions. If larger reductions are required, the additional inspection parameters, requiring more complex procedures, would be warranted. This implies that the design of a parameter inspection procedure should consider in an ordinal manner; idle adjustment inspection, ignition system inspection, and induction system inspection.

Since it depends upon checking the mechanical condition of the vehicle, rather than a direct evaluation of the vehicle's emission levels, the engine parameter approach would be less reliable in identifying vehicles with high emission levels than would an emission inspection approach. On the other hand, an engine parameter inspection approach can minimize the diagnosis required by the repair agency in contrast with an emission inspection whose results can provide only general guidelines for determining the proper repair actions. In addition, an emission inspection approach requires, in general, a reinspection of failed vehicles after maintenance to ensure compliance with the standards. In contrast, the results of an engine parameter test may specifically define the appropriate maintenance and, if the maintenance is properly performed, compliance with the parameter inspection requirement is achieved by definition. Reduced emissions of the repaired vehicle depend upon the validity of the relationship between the parameter evaluated and emission levels.

2.3 FEASIBILITY EVALUATION OF INSPECTION/MAINTENANCE PROGRAMS

This section presents a preliminary evaluation of the feasibility and the potential effectiveness of the inspection/maintenance strategy. The results of three independent studies are analyzed to characterize the attributes of exhaust emission inspection, engine parameter inspection, and mandatory maintenance. The evaluation of the first approach includes a study of both an idle mode emission inspection and a dynamic mode emission inspection.

The information set forth in the following discussion provides an assessment of the extent to which excessive emissions are caused by an inadequate level of maintenance for vehicles currently in service, the feasibility of identifying individual vehicles which achieve substantial emission reductions following maintenance, the capability of specifying the proper repair and adjustment procedures to achieve these reductions, the cost of emission-related maintenance, and the cost of implementing and operating the inspection program. The quantification of these characteristic parameters currently provides the only empirical basis for evaluating the potential impact of the inspection/maintenance strategy.

The salient observations are shown in Table 2-4 for each of the three inspection/maintenance approaches. The emission inspections and the engine parameter inspection were evaluated utilizing composite test fleets which were statistically representative of the current vehicle population with respect to the distribution by model year, emission control groups, manufacturer, and engine size. Every vehicle in the sample fleet was tested using the appropriate inspection procedure, and those failing

TABLE 2-4

FEASIBILITY STUDIES OF THE INSPECTION/MAINTENANCE STRATEGY

Strategy Design	Number of Vehicles in Test Fleet	Initial Reduction of Fleet Mean Exhaust Emissions*			Serviced Vehicles (% of Test Fleet)	Anticipated Inspection Cost per Vehicle	Average Repair Cost per Serviced Vehicle
		HC	CO	NOx			
Exhaust Emission Inspection	600	25%	19%	0+	50%	$1.25	$28.50
Engine Parameter Inspection	450	11%	6.5%	0+	~ 95%	$7.50	$22.00
Mandatory Maintenance	85	15%	11%	0+	100%	NA	$55.00

* Exhaust emissions measured using 1972 (CVS-C) Federal Test Procedure.

+ Change in NOx emissions statistically insignificant.

the inspection standards received diagnosis and maintenance according to the defined methodology of the test program. The third alternative (mandatory maintenance) was evaluated using only pre-emission controlled vehicles. In this case, there is no inspection required; every vehicle receives identical maintenance wherein specific engine adjustments are required and specific engine components are replaced.

A description of the study methodology and a more definitive evaluation of the observations for each test program are presented in the following text.

2.3.1 EXHAUST EMISSION INSPECTION

Two representative exhaust emission test procedures were independently evaluated in a preliminary pilot study. The idle mode test and a loaded cruise mode test were selected as the inspection procedures for two separate vehicle test fleets composed of privately-owned automobiles. Each sample fleet was tested using the appropriate inspection procedures, and those vehicles which did not comply with the emission standards were repaired in accordance with the objective of reducing exhaust emission levels.

Hereafter, this test program will be referred to as the Short Cycle Study. 7

STUDY METHODOLOGY

The purpose of the Short Cycle Study was to determine, as accurately as possible, the effects which could be expected immediately following the actual implementation of an enforced emission inspection/maintenance program. Accordingly, the sample fleet was composed of privately-owned vehicles randomly selected in such a manner as to ensure that it was statistically representative of the real vehicle population.

Private service garages and independent automobile dealerships were solicited to participate in the program to provide the necessary repairs for those vehicles which failed the inspection standards. The service facilities were selected to provide a representative cross section of the present maintenance industry. The test program was duplicated in two geographic areas to evaluate the existence of any potential differences which may occur among regional vehicle populations and regional automotive service industries.

The idle mode emission test and a constant velocity cruise mode emission test were used to evaluate the effectiveness of alternative inspection procedures. These two particular procedures were selected to assess the range of the impact which can be expected as a result of measuring emissions during loaded operation of the engine, versus measuring emissions from a free running engine with no external loading imposed. The evaluation of the two procedures was carried out independently using separate vehicle sample fleets and separate groups of repair facilities. The vehicle selection was matched to ensure that the two test fleets were statistically equivalent.

The emission test sequence which was performed for every vehicle in both inspection fleets was designed to provide three types of information. The Federal Test Procedure was used to provide a measure of the true mass emission level and was the defined performance standard for evaluating the impact of the program, the inspection test measurement provided the information necessary to identify excessively emitting vehicles which were to receive maintenance, and numerous additional short test emission measurements were made to obtain data to evaluate the range of correlation which can be achieved between the Federal Test Procedure and the various emission tests which are considered feasible alternatives for the inspection process. The correlation analysis will be discussed in greater detail in Section 2.5.

The effectiveness measure which defined the performance of the inspection/maintenance programs is the change in the total fleet mean emission level of HC, CO, and NO_x, as measured by the FTP. Although NO_x emissions were not used as failure criteria, the impact of the program upon this emission species was evaluated to assess the potential deleterious ffects on NOx typically associated with tune-up procedures designed to reduce HC and CO.

The idle mode inspection fleet used standard procedures for the volumetric measurement of HC and CO during free running idle operation. The vehicle was tested with the transmission in neutral. A vehicle failed the inspection if it exceeded the emission standards for either HC or CO.

The cruise mode inspection fleet was tested using the Key Mode[2] test procedure as described in Section 2.2.1. The loading imposed on the engine during the low and high cruise modes varies according to the weight class of the vehicle. The load factor is controlled by altering the simulated speed for the vehicle being tested. Table 2-5a shows the speed and load factors for the different weight classes.

The emission standards were selected to fail approximately 50% of each test fleet. A vehicle failed the inspection if it exceeded the emission standard for either HC or CO in any test mode.

The emission failure criteria for the Idle Mode fleet and the Key Mode fleet are summarized in Table 2-5b.

Following maintenance, the failed vehicles were retested using the complete test sequence described earlier. If the vehicle again failed to comply with the inspection standards, it was returned to the service garage for additional maintenance. Failure following the second service resulted in the termination of the vehicle and a complete diagnosis to determine the cause of the failure. If at any point in the test program the vehicle was shown to require repairs exceeding $100, the vehicle was terminated without performing the repair. The emission test data remained in the fleet statistics, and the vehicle was diagnosed to determine the cause of failure. The flow diagram in Figure 2-2 outlines the operational design of the test program.

The repair facilities were selected to represent average capabilities within the service industry in the two regions. Prior to initiating the

TABLE 2-5a

LOAD AND SPEED FACTORS FOR KEY MODE TEST

	Low Cruise Mode		High Cruise Mode	
Weight Class	Speed	Load	Speed	Load
Less than 2800 lbs	23 mph	5 hp	37 mph	14 hp
2800-3800 lbs	30 mph	9 hp	45 mph	23 hp
Greater than 3800 lbs	33 mph	11 hp	49 mph	29 hp

TABLE 2-5b

FAILURE CRITERIA FOR SHORT CYCLE STUDY

Inspection Fleet	Test Mode	Pre-Emission Controlled Vehicles		Emission Control Vehicles			
				Air Injection		Engine Modification	
		HC	CO	HC	CO	HC	CO
California							
Key Mode	Idle	825 ppm	7.0%	300 ppm	4.0%	375 ppm	4.5%
	Low Cruise	525 ppm	4.2%	300 ppm	2.75%	300 ppm	2.75%
	High Cruise	525 ppm	3.4%	300 ppm	2.5%	300 ppm	2.5%
Idle Mode	Idle	700 ppm	6.5%	250 ppm	3.5%	325 ppm	4.0%
Michigan							
Key Mode	Idle	800 ppm	7.2%	300 ppm	4.0%	400 ppm	5.0%
	Low Cruise	550 ppm	4.5%	300 ppm	2.8%	300 ppm	2.8%
	High Cruise	550 ppm	3.5%	300 ppm	2.5%	300 ppm	2.5%
Idle Mode	Idle	700 ppm	8.0%	250 ppm	3.8%	350 ppm	5.5%

FLOW DIAGRAM
of
SHORT CYCLE STUDY

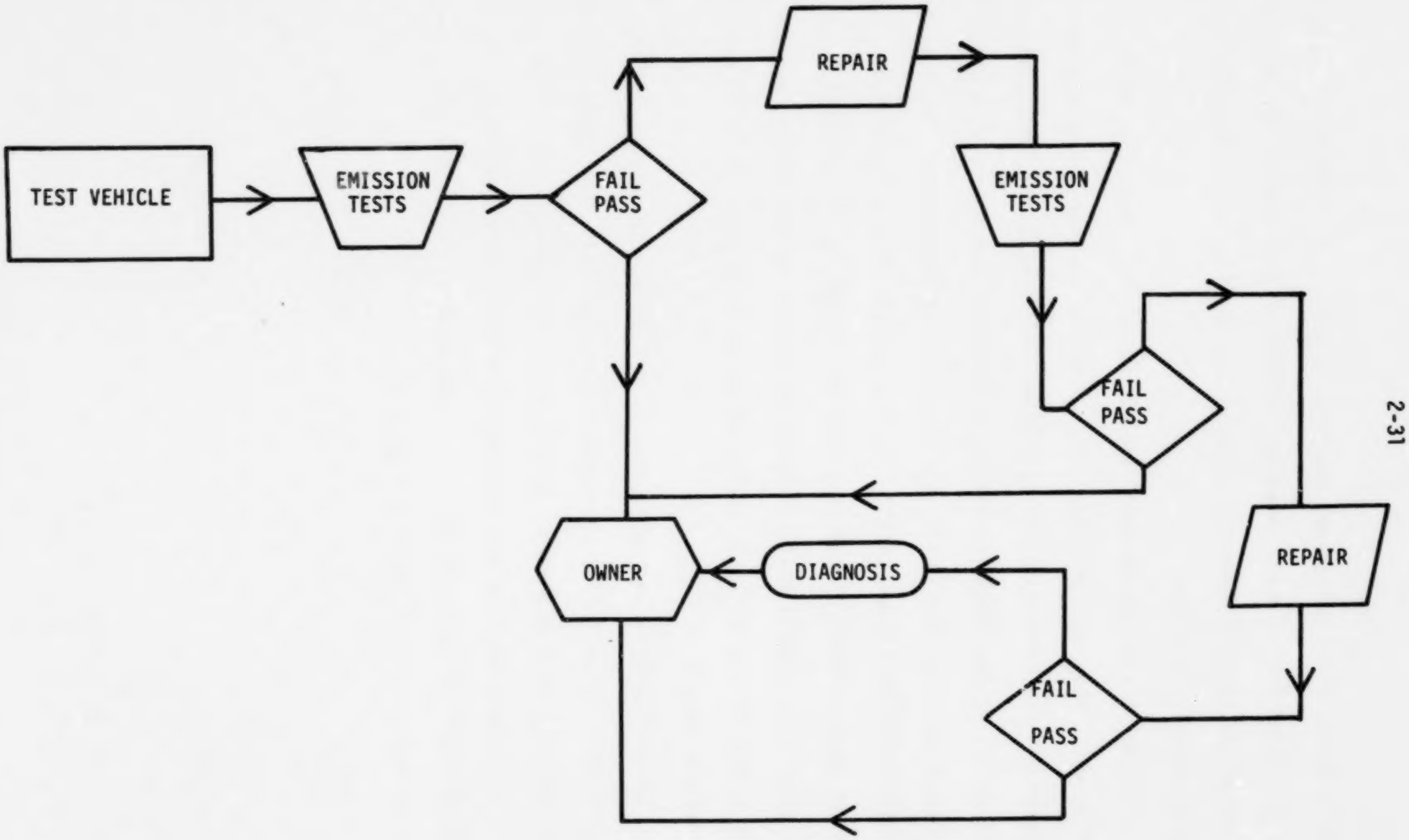

TEST VEHICLE
EMISSION TESTS
FAIL
PASS
REPAIR
EMISSION TESTS
FAIL
PASS
REPAIR
FAIL
PASS
DIAGNOSIS
OWNER

FIGURE 2-2

test program, every garage was assigned to work with vehicles from one of the two inspection fleets. Adequate provisions were made to ensure that every garage in both inspection regions had an infrared hydrocarbon and carbon monoxide analyzer.

The service mechanics were required to attend a briefing session during which they were provided with the guidelines for the maintenance program and the administrative requirements. In addition, they were given instruction in the causes of excessive emissions and the relationship between excessive emission levels and specific engine malfunctions. The briefing sessions were held independently for the garages associated with each of the two test fleets. The garages were instructed in the interpretation of the diagnostic content of the respective inspection procedures, and the limitations on the types of repairs which could be justified with each inspection test.

The test program was duplicated in two phases; the purpose of the second phase was primarily to expand the sample size. The study methodology was identical in both phases. During Phase II, however, a new group of service garages was used and the failure criteria were lowered to obtain a greater number of serviced vehicles. The sample size for the test fleets and various sub-groups are shown in Figure 2-3.

VEHICLE SAMPLE DISTRIBUTION
for
SHORT CYCLE STUDY

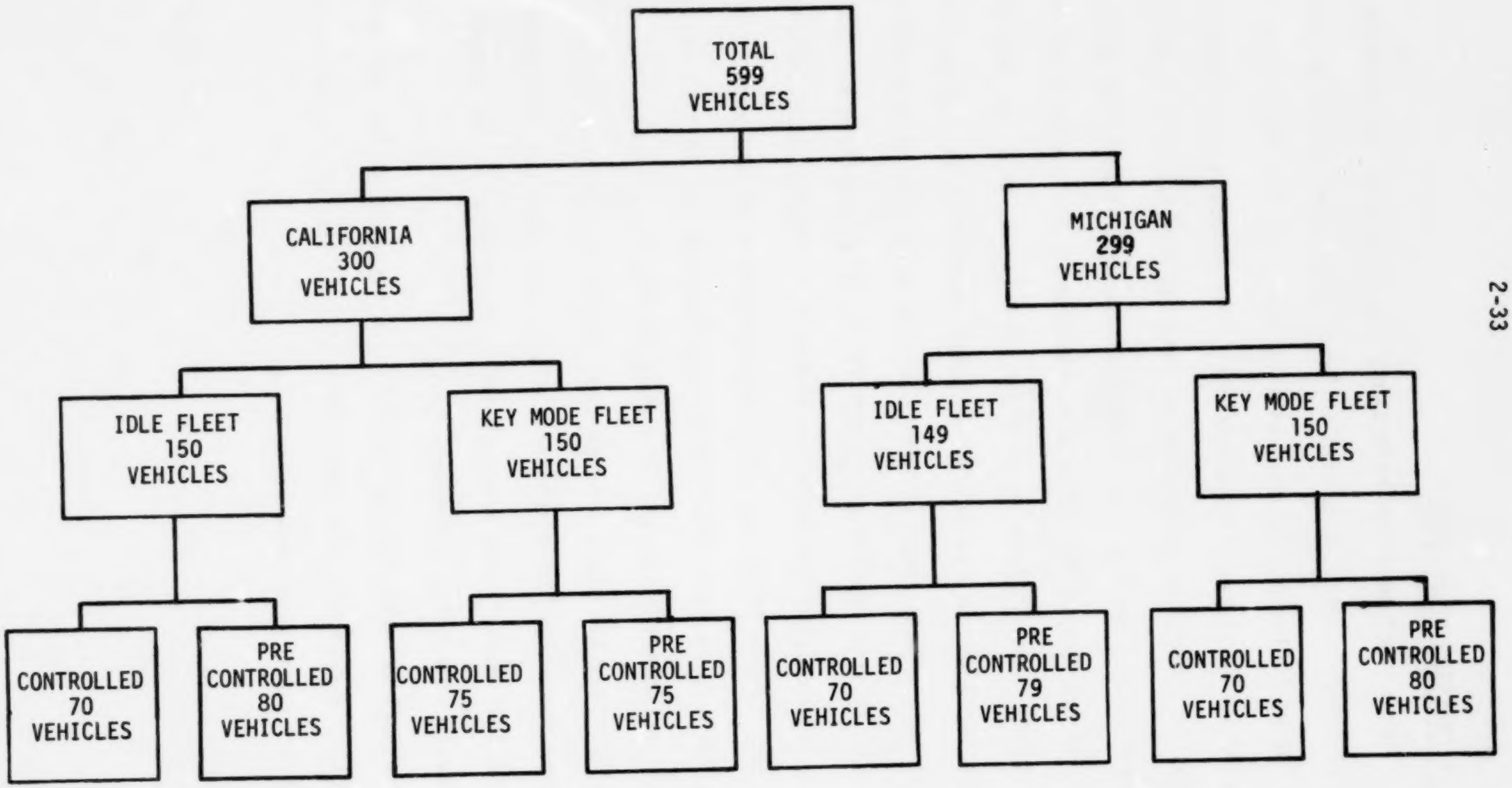

TOTAL 599 VEHICLES
CALIFORNIA 300 VEHICLES
MICHIGAN 299 VEHICLES
IDLE FLEET 150 VEHICLES
KEY MODE FLEET 150 VEHICLES
IDLE FLEET 149 VEHICLES
KEY MODE FLEET 150 VEHICLES
CONTROLLED 70 VEHICLES
PRE CONTROLLED 80 VEHICLES
CONTROLLED 75 VEHICLES
PRE CONTROLLED 75 VEHICLES
CONTROLLED 70 VEHICLES
PRE CONTROLLED 79 VEHICLES
CONTROLLED 70 VEHICLES
PRE CONTROLLED 80 VEHICLES

FIGURE 2-3

FLEET EMISSION REDUCTIONS

The initial emission reductions resulting from maintenance of the failed vehicles are summarized in Table 2-6. Each emission reduction reflects the change in the pooled mean emission level of the total test fleet, or vehicle sub-group, as appropriate. For purposes of comparison, the composite reductions of the pooled data for the combined inspection fleets in each State, and the total composite reductions are also presented.

The 90% confidence intervals, based upon the variance of the fleet emission reductions, are illustrated in Figure 2-4 (a, b, & c) for hydrocarbons, carbon monoxide, and oxides of nitrogen respectively. These intervals are an estimate of the range of effectiveness which can be expected to occur for the real vehicle population at the 90% level of confidence. This uncertainty in the test results reflects the inherent risk associated with the assumption that each sample fleet was truly representative of the vehicle population.

There is no significant difference between the initial emission reductions observed for the Idle Mode and Key Mode fleets tested in Michigan. In California, the mean, or expected, initial reductions observed for the Key Mode test fleet were substantially larger than the reductions observed for the Idle Mode fleet; although the current data do not support such a hypothesis at the 90% confidence level.

To further evaluate the initial effectiveness of the two emission inspection approaches, the characteristics of the inspection and maintenance phases are considered separately below.

TABLE 2-6

SHORT CYCLE STUDY EMISSION REDUCTIONS

TEST REGIME	VEHICLES SERVICED	MEAN REDUCTION OF EXHAUST EMISSIONS HC	CO	NOx+
CALIFORNIA TEST FLEET	50%	29%	20%	6.5%
Idle Mode Inspection Regime	44%	23%	15%	0
Pre-1966 Vehicles	53%	24%	16%	0
Post-1966 Vehicles	34%	14%	14%	- 2.5%
Key Mode Inspection Regime	56%	34%	24%	-13.0%
Pre-1966 Vehicles	61%	38%	29%	-21.0%
Post-1966 Vehicles	52%	26%	21%	- 8.0%
MICHIGAN TEST FLEET	50%	23%	19%	- 2.5%
Idle Mode Inspection Regime	50%	21%	19%	- 5.0%
Pre-1968 Vehicles	50%	25%	18%	0
Post-1968 Vehicles	50%	16%	20%	- 8.7%
Key Mode Inspection Regime	49%	22%	18%	0
Pre-1968 Vehicles	54%	27%	17%	3.0%
Post-1968 Vehicles	44%	14%	20%	- 2.4%
Composite Total	50%	25%	19%	- 4.0%

+ Negative reduction indicates an emission increase. NO_x changes were not statistically significant.

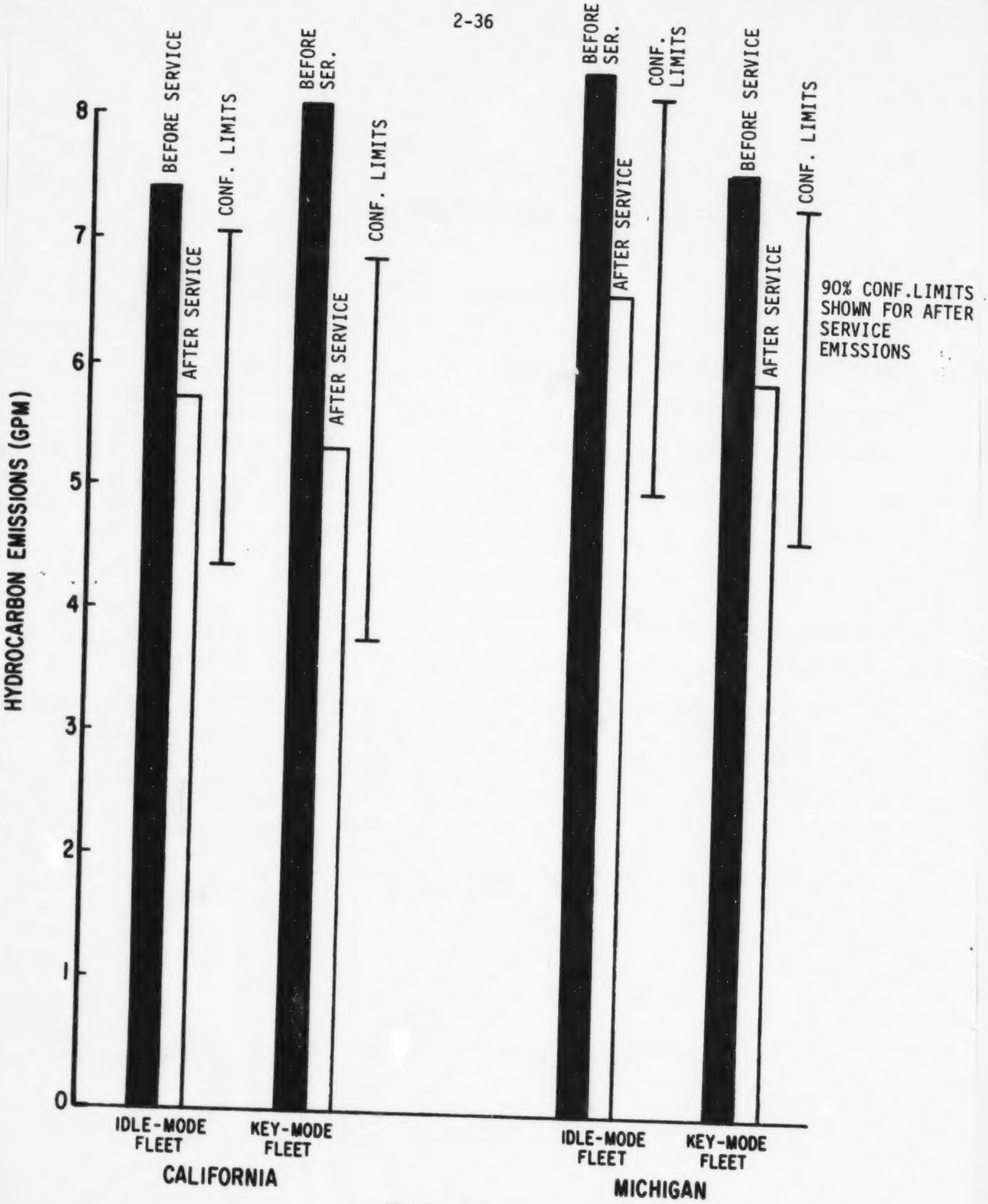


FIGURE 2-4a
SHORT CYCLE STUDY EMISSIONS
BEFORE AND AFTER SERVICE

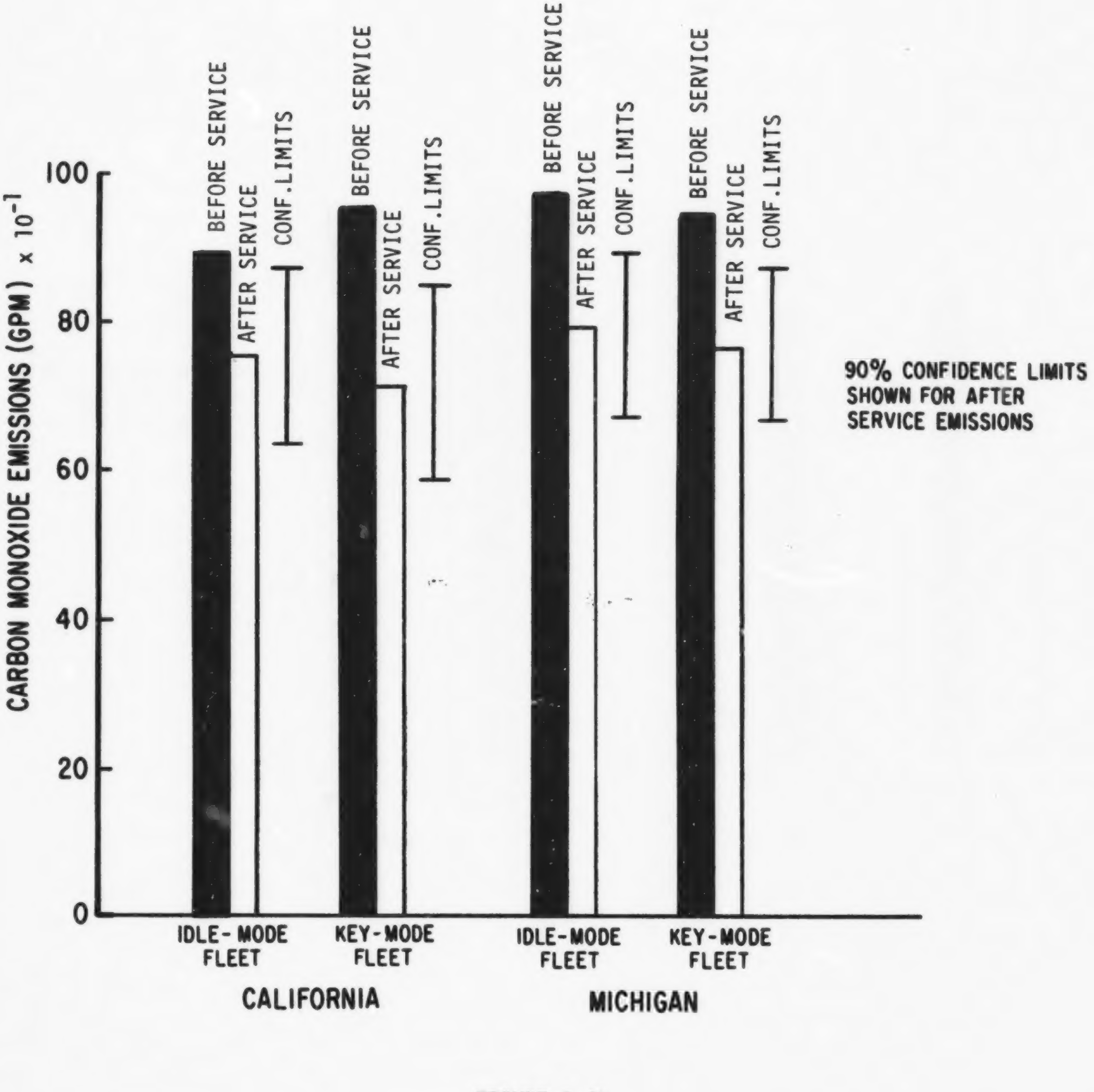


FIGURE 2-4b

SHORT CYCLE STUDY EMISSIONS
BEFORE AND AFTER SERVICE

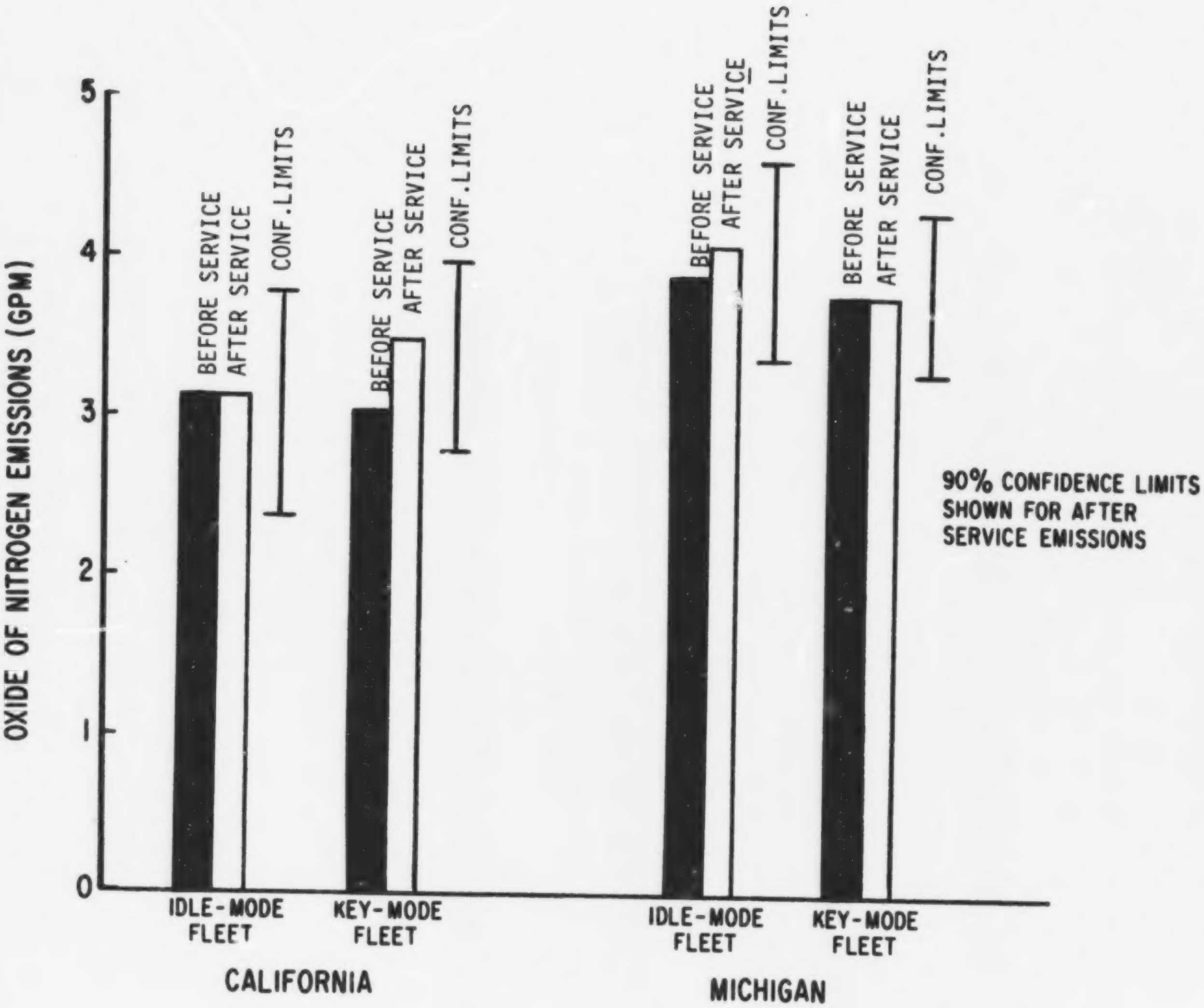


FIGURE 2-4c

SHORT CYCLE STUDY EMISSIONS
BEFORE AND AFTER SERVICE

FAILED VEHICLE CHARACTERISTICS

The test failures within each fleet were evaluated in order to characterize the nature of the serviced vehicle sub-group identified by the two inspection techniques. The incidence of failures due to excessive HC and/or CO emissions within each test mode is summarized in Table 2-7. The results are shown individually for the two inspection fleets in each State, and a composite distribution is shown for each inspection approach by combining the appropriate inspection fleet data for the two States.

Among all of the fleets tested in the study, excessive CO emissions in the idle mode was seen to be the most prevalent type of failure; about 70% to 80% of the failed vehicles had idle mode CO emissions in excess of the inspection standards. Excessive idle mode HC levels were observed for as many as 50% of the vehicles failed in the various fleets. Excessive HC or CO levels in the cruise modes were found in about 35% to 45% of the failed vehicles; but in nearly all cases, excessive cruise mode emission levels ocurred in conjunction with excessive emission levels in the idle mode. In an average of only 4% of the cases were vehicles failed only on the basis of excessive cruise mode CO levels; and the number of vehicles failed only because of excessive HC emissions in the cruise modes was insignificant.

A potential advantage of a loaded mode inspection test over one which measures emissions only in the idle mode is the ability of cruise mode testing to identify vehicles having malfunctions which are evidenced only when the vehicle engine is under load. Partial blockage of the air cleaner and certain types of ignition system failures are typical of this. However, the above analysis indicates that, for the vehicle fleets tested, approximately 95% of the vehicles failed using the Key Mode inspection approach would also have been failed had only an Idle Mode inspection been performed.

TABLE 2-7

FLEET FAILURE CHARACTERISTICS

FAILURE MODE	ALL VEHICLES (% of failures)			CALIFORNIA VEHICLES (% of failures)			MICHIGAN VEHICLES (% of failures)		
	HC Only	CO Only	HC & CO	HC Only	CO Only	HC & CO	HC Only	CO Only	HC & CO
Idle Mode Inspection Fleet									
Idle Mode	25	52	23	20	54	26	28	48	23
Key Mode Inspection Fleet									
Idle Mode only	4	44	13	5	35	9	4	54	16
Cruise Mode only	0	4	0	0	6	0	0	1	0
Idle & Cruise Mode	5	14	15	7	16	16	1	12	11

This explains partially why similar initial emission reductions were observed for both the Idle Mode and Key Mode fleets, since both inspection approaches selected essentially equivalent groups of vehicles to be subjected to maintenance. However, substantial changes in the prevalence of cruise-mode-only failures, as might result when an idle emission inspection program ensured maintenance of idle parameters without necessarily causing power system malfunctions to be corrected, would result in significant differences between the vehicle groups failed by idle and loaded mode inspection tests.

MAINTENANCE AND DIAGNOSTIC PERFORMANCE

Ultimately, an inspection/maintenance program can accomplish a reduction in vehicular emissions only to the extent that it causes more and/or better vehicle maintenance to be performed than would have occurred voluntarily. Clearly, the quality of the maintenance performed in response to an emission inspection failure will have an important impact on the effectiveness and cost of the inspection/maintenance program. The performance of the service garages participating in the Short Cycle Study has been evaluated from two diametric viewpoints. One has considered the extent to which the repair agencies were capable of performing maintenance which would permit the vehicles to comply with the inspection standards and, thereby, achieve the primary goal of reducing exhaust emissions; and the second, the extent of excessive repair, and the resultant unnecessary cost burden, which can be attributed to poor diagnostic performance.

The adequacy of the maintenance may be judged by considering the test history of the failed vehicles following the first and second service events for the Key Mode test fleets and the Idle Mode test fleets, which is shown in Table 2-8. The maintenance performance is determined to be

TABLE 2-8

EFFECTIVENESS OF MAINTENANCE RESPONSE

INSPECTION/SERVICE	CORRECT REPAIR TERMINATE PASS	INCORRECT REPAIR SECOND SERVICE REQUIRED	INCORRECT REPAIR TERMINATE FAIL	MAJOR MECHANICAL TERMINATE FAIL
Key Mode Inspection				
First Service	66%	20%	5%	8%
Second Service	11%		8%	2%
Idle Mode Inspection				
First Service	72%	13%	8%	7%
Second Service	8%		5%	

adequate only on the basis of the inspection criteria; if the vehicle complies with the standards, the repair action is considered satisfactory. Approximately 70% of the failed vehicles in both inspection fleets received sufficient maintenance during the first servicing to comply with the inspection standards on retest. About 10% more passed after a second servicing. 13% of the initial failures received inadequate diagnosis and were terminated as failures. In general, these vehicles were judged to have been capable of achieving compliance with reasonable maintenance; however, the excess cost incurred due to the inadequacy of the diagnosis prevented their repair for $100 or less. The remaining 7% to 10% of the failures required major repairs in excess of $100.00. These vehicles were terminated as failures and judged to be unservicable.

The second consideration in analyzing the repair actions requires an assessment of the excessive or unjustified maintenance. Initially, the test program personnel conducted a diagnosis of the inspection failures to identify the maintenance actions which would be necessary to comply with the emission standards. The repair action of the service garages was then analyzed and a determination of excess repair was made. Table 2-9 summarizes the maintenance requirements for each inspection fleet. Table 2-10 summarizes the actual incidence of excessive repair that was identified for the following maintenance categories:

TABLE 2-9

DIAGNOSIS OF FAILED VEHICLES

INSPECTION FLEET	REQUIRED MAINTENANCE				
	Idle Adjustment	Ignition System Repair	Carburetor Repair	Ignition System & Carburetor Repair	Other*
Key Mode Fleet (% of failures)	65%	3%	21%	1%	12%
Idle Mode Fleet (% of failures)	82%	4%	6%	1%	8%

* Includes parts replacement and major mechanical repair.

TABLE 2-10

EXCESSIVE REPAIR SUMMARY

INSPECTION FLEET/ TEST PHASE	Frequency of Vehicles with Excess Repair	Minor Adjustment	Minor Replacement	Carburetor Repair	Ignition System	Major Mechanical
Key Mode Inspection Phase One	50%	---	3%	12%	38%	0
Phase Two	22%	1%	---	4%	18%	0
Idle Mode Inspection Phase One	36%	---	---	4%	33%	0
Phase Two	32%	1%	---	6%	25%	0

*Minor Adjustment - routine idle adjustment of the carburetor and distributor.

*Minor Replacements - replacement of minor parts such as the air filter, PCV valve, heat riser, vacuum lines, gaskets, etc.

*Carburetor - repair, rebuild, or replace the carburetor.

*Major Ignition Tuneup - replacement of plugs, points, condenser, distributor, and associated adjustments.

*Major Mechanical - major work involving the repair or replacement of items such as rings, valves, etc. up to a total of $100 for parts and labor.

The guidelines for the test program required that any vehicles needing repair work in excess of $100.00 be classified as unservicable and terminated from the program. The exhaust emission data, however, remained in the fleet statistics.

The maintenance requirements identified in Table 2-9 exhibit the same trends observed for the modal failure characteristics shown in Table 2-7. The incidence of excessive idle mode emissions was the predominant cause for failure; therefore, the need for idle adjustment would logically be expected to dominate the other repair categories.

The frequency of excessive repair is presented individually for Phase One and Phase Two of the test program. Prior to initiating Phase Two, a second group of service garages was selected for participation in the test program. The orientation and instruction techniques were re-evaluated in an attempt to ensure that the maintenance personnel understood the diagnostic capability of the emission tests. An effort was also made to stress the importance of minimizing unjustifiable repairs.

The total incidence of excessive repair was highest for the Key Mode inspection fleet during Phase One. A comparison of the ignition system maintenance required (Table 2-9) and the associated incidence of excess repair indicates that extensive impact is incurred from this repair category alone. This observation is attributed to a strong tendency for the maintenance personnel to rely upon conventional maintenance practices for repairing the individual vehicles.

The effort to improve the garage performance during Phase Two effected a substantial improvement for the Key Mode fleet, reducing the frequency of excess repair by more than one-half. The change observed for the Idle Mode fleet was insignificant. This effect would be expected, based upon the assumption that excess repair among the Idle Mode service garages results from the insufficient diagnostic content of the idle emission test. The excess repair performed by the Key Mode service garages would be attributed to an inadequate diagnostic interpretation of the test results.

COST OF EMISSION-RELATED REPAIR

One factor in the cost of an inspection/maintenance program is the cost of the maintenance required for the vehicles failed by the inspection test. This cost includes both the cost for diagnosing the failed vehicles to determine how to bring them into compliance with the inspection standards, and the cost for labor and parts to perform those repair actions. In practice, the out-of-pocket cost for repair of failed vehicles will probably exceed the net additional maintenance cost imposed by the inspection/maintenance program, since some of the maintenance performed on failed vehicles is likely to substitute for voluntary maintenance which would otherwise have been performed. The effect on net inspection/maintenance program cost of substitution of required maintenance for voluntary maintenance is discussed in Section 2.4; the maintenance cost figures presented in this section refer only to the actual incurred costs for repair of failed vehicles.

Table 2-11 summarizes the maintenance costs per serviced vehicle observed in each phase of the Short Cycle Study for both the Idle Mode and Key Mode inspection fleets. In addition to the actual incurred cost, a corrected cost is presented for each fleet and phase which has been derived from the incurred cost by subtracting the cost of the excessive repair identified in Table 2-9. Averaged over both phases of the study, the cost of excessive maintenance represents about 30% of the observed cost for both inspection fleets.

In all categories, the Key Mode fleet service costs were higher than those for the Idle Mode fleet; when both were corrected for excessive repair, the Key Mode maintenance costs averaged about 20% higher than those for the Idle Mode fleet. This observation is not unexpected, since the diagnostic capabilities of the loaded mode test provide justification for more comprehensive, and generally more costly, repair actions.

To facilitate comparison with other in-use vehicle emission control approaches, the maintenance costs are also presented as an average cost per vehicle in the fleet, including both serviced and non-serviced vehicles. It can be seen from Table 2-11 that the average maintenance cost per vehicle in the fleet might be expected to range from about $9 to $14, depending on the inspection approach and the extent of excessive repair.

TABLE 2-11

MAINTENANCE COST SUMMARY

	Composite Idle Mode Fleet		Composite Key Mode Fleet	
	Incurred Cost	Corrected Cost	Incurred Cost	Corrected Cost
Phase One ($ per serviced vehicle)	$27.10	$18.06	$32.40	$22.96
Phase Two ($ per serviced vehicle)	$24.51	$17.55	$25.42	$20.19
Total Test Program ($ per serviced vehicle)	$25.52	$17.75	$28.50	$21.41
Total Fleet Average ($ per vehicle)	$12.76	$ 8.88	$14.25	$10.70

INSPECTION COSTS

In addition to the cost for maintenance of vehicles failed by an inspection/maintenance program, the costs associated with inspecting the vehicle population must be evaluated. These costs include both the investment costs to provide inspection facilities and equipment, and operating costs for carrying out the inspections and administering the inspection/maintenance program.

There are two basic types of inspection system configurations which may be considered: State-operated inspection lanes, which would be devoted exclusively to vehicle inspection activities on a high-throughput basis; and licensed private garages, which would conduct emission inspections in addition to their normal maintenance and repair activities.

In a licensed private garage system, the inspection cost per vehicle will depend strongly upon the number of vehicles inspected per garage and the administrative costs; these, in turn, will depend upon the size and regional distribution of the vehicle population, the number of garages licensed, and the possible previous existence of an administrative framework for safety inspection. Since these factors will vary significantly among the regions which may be considering the implementation of emission inspection programs, cost estimates for licensed private garage systems must be made on a regional basis and no generally applicable inspection cost data for such approaches can be presented here. Estimates which have been made in specific cases range from about $3 to $6 per vehicle for an idle mode emission inspection.[8]

Table 2-12 presents estimates of the investment and annual operating costs for State-operated inspection lanes using the Idle Mode and Key Mode procedures. Estimates for both approaches provide for semi-automated

TABLE 2-12

Inspection Station Cost Estimates[8]

Cost Element	Station Type			
	Idle Mode		Key Mode	
Investment Costs	1 lane	2 lane	1 lane	2 lane
Inspection Equipment	$11,200	$22,400	$14,000	$28,000
Administration	$ 1,000	$ 1,700	$ 1,000	$ 1,700
Site Acquisition ($2/sq. ft.)	$14,380	$20,000	$21,800	$30,220
Construction ($8/sq. ft.)	$10,960	$16,320	$16,320	$24,480
TOTAL	$37,540	$60,420	$53,120	$84,000
Operating Cost (1st year)				
Personnel Salaries	$22,000	$44,000	$22,000	$44,000
Supplies & Maintenance	$ 1,748	$ 3,186	$ 2,216	$ 3,994
TOTAL	$23,748	$47,186	$24,216	$47,994

Annual Capacities of Inspection Lanes: Idle Mode - 32,000 vehicles/lane
Key Mode - 25,000 vehicles/lane

processing of emission test data. Since the data acquisition systems are the major equipment cost and both test regimes require similar data acquisition systems, the equipment investment costs per lane for the Idle Mode and Key Mode inspection approaches differ by only about 20%. Labor is seen to be the predominant operating cost and this is considered to be the same per lane for both the Idle Mode and Key Mode approaches. In comparing the total costs of inspection programs using the two approaches, however, the higher capacity of the Idle Mode lanes must be taken into account.

Regional cost estimates for an inspection program must include additional expenditures required for training inspection personnel, program planning, and the initial qualification and certification of the inspection facilities. The operating cost element must also consider the maintenance and depreciation of the inspection facilities, and the total system administration and enforcement requirements.

An operational analysis of the inspection station design for each test procedure, and an analysis of the distribution of vehicle population densities was performed for the State of California.[8] The total program cost elements are summarized in Table 2-13. The testing capacity of the inspection system is based on a yearly inspection of the total California population of 10 million vehicles.

TABLE 2-13

Total Program Costs +
(Thousands of Dollars)

Cost Element	Idle Mode	Key Mode
Investment Costs		
Site Acquisition & Construction	7,117 (59)*	12,445 (63)
Equipment & Installation	4,090 (33)	6,270 (32)
Planning & Training	112 (1)	193 (1)
Qualification & Certification	745 (7)	912 (4)
TOTAL	12,064	19,820
Operating Cost (1st year)		
Salaries of Inspection Personnel	6,635 (67)	6,648 (61)
Salaries of Administrative Personnel	631 (7)	981 (9)
Equipment Maintenance & Depreciation	1,214 (12)	1,473 (14)
Facility Maintenance & Depreciation	256 (2)	516 (4)
Program Administrative Costs	1,243 (12)	1,301 (12)
TOTAL	9,979	10,919

*Percentage of Total
+Estimated for California vehicle population (10 million)

The initial investment burden of the inspection system can potentially be pre-financed by increasing the vehicle registration fee prior to the program implementation; alternatively, the total investment can be amortized on a fixed capital return schedule. Table 2-14 compares the initial investment cost and the annual capital return schedule required for the two test regimes in the example discussed above.

TABLE 2-14

DISTRIBUTED ANNUAL INVESTMENT RETURN

	Idle Mode Inspection		Key Mode Inspection	
	Total (Thousands)	Cost per Vehicle Test	Total (Thousands)	Cost per Vehicle Test
Total Investment	$12,064	$1.21	$19,820	$1.98
Annual Capital Return*	$ 2,160	$ .22	$ 3,549	$0.35

*Capital investment amortized over 10 years at 6%.

Discounting the annual capital return plus the inflated annual operating cost for the first ten years of operation yields an average annual cost per vehicle test in 1972 dollars. The average annual cost figures are $1.04 for the Idle Mode test and $1.22 for the Key Mode test.

Assuming that a retest would be required following maintenance, the cost per vehicle test should be proportionately scaled to account for the failure rate. This provides an estimate of the average annual cost per vehicle which facilitates a more convenient estimate of regional costs.

The estimated annual cost per vehicle is assumed to be valid for any region which has a vehicle population density and an urban-rural distribution similar to that of California. The validity of this assumption relies on the dominance of the total system cost by the labor cost element. Because the total labor time is directly proportional to the number of vehicles subject to the inspection, an estimate of the total program cost may be calculated based on the regional vehicle population and the annual vehicle cost for the appropriate inspection procedure.

2.3.2 ENGINE PARAMETER INSPECTION

The engine parameter inspection requires a functional test of specific engine components and adjustable parameters which are determined to have a significant effect upon vehicle emissions, and which exhibit an extensive rate of deterioration. As a general class, the engine parameter inspection technique may include any combination of diagnostic procedures for emission related subsystems of the engine. In addition to selecting the most cost-effective parameters to be tested, the optimal design of an inspection policy requires a determination of the appropriate failure criteria.

FLEET EMISSION REDUCTION

The data presented in this section are applicable to the extensive engine parameter inspection which was described in Section 2.2. Both the inspection and resultant maintenance were performed by an experienced emission testing laboratory. Table 2-15 summarizes the results for each control group. The 1971 California vehicles are listed separately to reflect the new control mechanisms which were incorporated to comply with the California emission standard for oxides of nitrogen.

The large number of individual parameters that were inspected resulted in the extremely high rejection rate, although many vehicles only required very minor adjustments.

Figures 2-5 (a&b) present the 90% confidence intervals for the fleet mean exhaust emissions after maintenance. HC and CO emissions are shown for the three separate control groups. The data indicate that the engine parameter inspection approach acheived a significant reduction of HC emissions at the 95% confidence level, whereas CO emissions were not significantly reduced above the 80% confidence level. The change in NOx emissions was not statistically significant.

TABLE 2-15

INITIAL EFFECTIVENESS OF ENGINE PARAMETER INSPECTION/MAINTENANCE

Test Fleet	Rejection Rate (Percent)	Exhaust Emissions* HC	CO	NOx
Pre-Control Vehicles	95			
As Received (gpm)		11.94	130	3.97
After Inspection and Maintenance (gpm)		10.80	122	4.22
% Reduction		9.5%	6.2%	-6.3%**
1966-1970 Control Vehicles	95			
As Received (gpm)		7.26	86.6	6.34
After Inspection and Maintenance (gpm)		6.24	80.5	6.50
% Reduction		14%	7%	-2.5%**
1971 NOx Control Vehicles	95			
As Received (gpm)		4.43	63.4	6.00
After Inspection and Maintenance (gpm)		4.36	59.2	5.88
% Reduction		1.6%	6.6%	2.0%**

* As measured by 1972 Federal Certification Test Procedure.

** A negative reduction represents an increase. NOx changes were not statistically significant.

ESTIMATED VEHICLE OWNER COSTS

The cost elements for the parameter inspection are attributed to the inspection time required for the engine diagnosis and the labor and parts required for proper maintenance. The labor cost is based on a burdened overhead rate of $10 per hour. It is assumed that the inspection system would be composed of existing privately owned automobile service facilities licensed by the state.

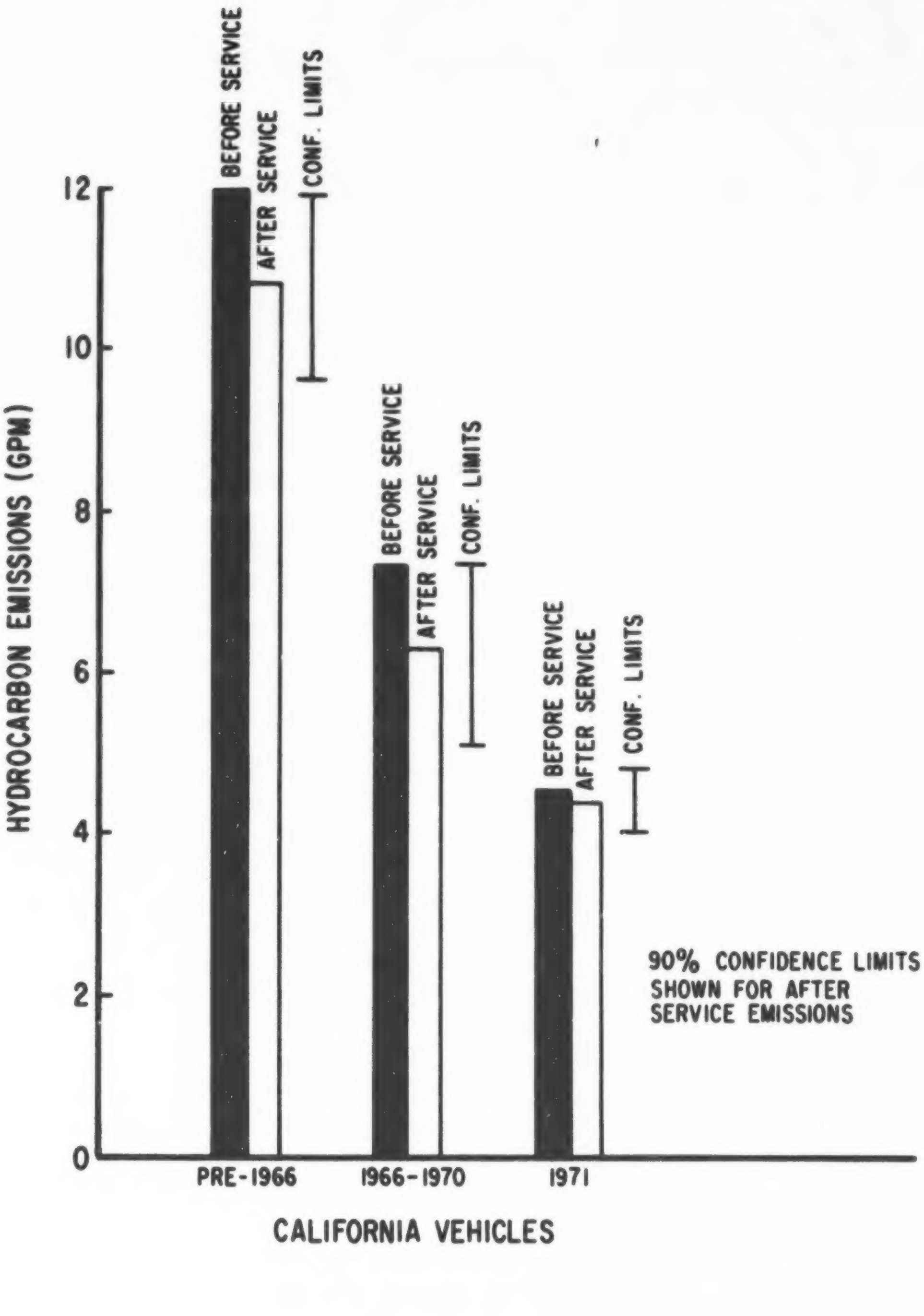


FIGURE 2-5a

FLEET EMISSIONS BEFORE AND AFTER
SERVICE ENGINE PARAMETER INSPECTION

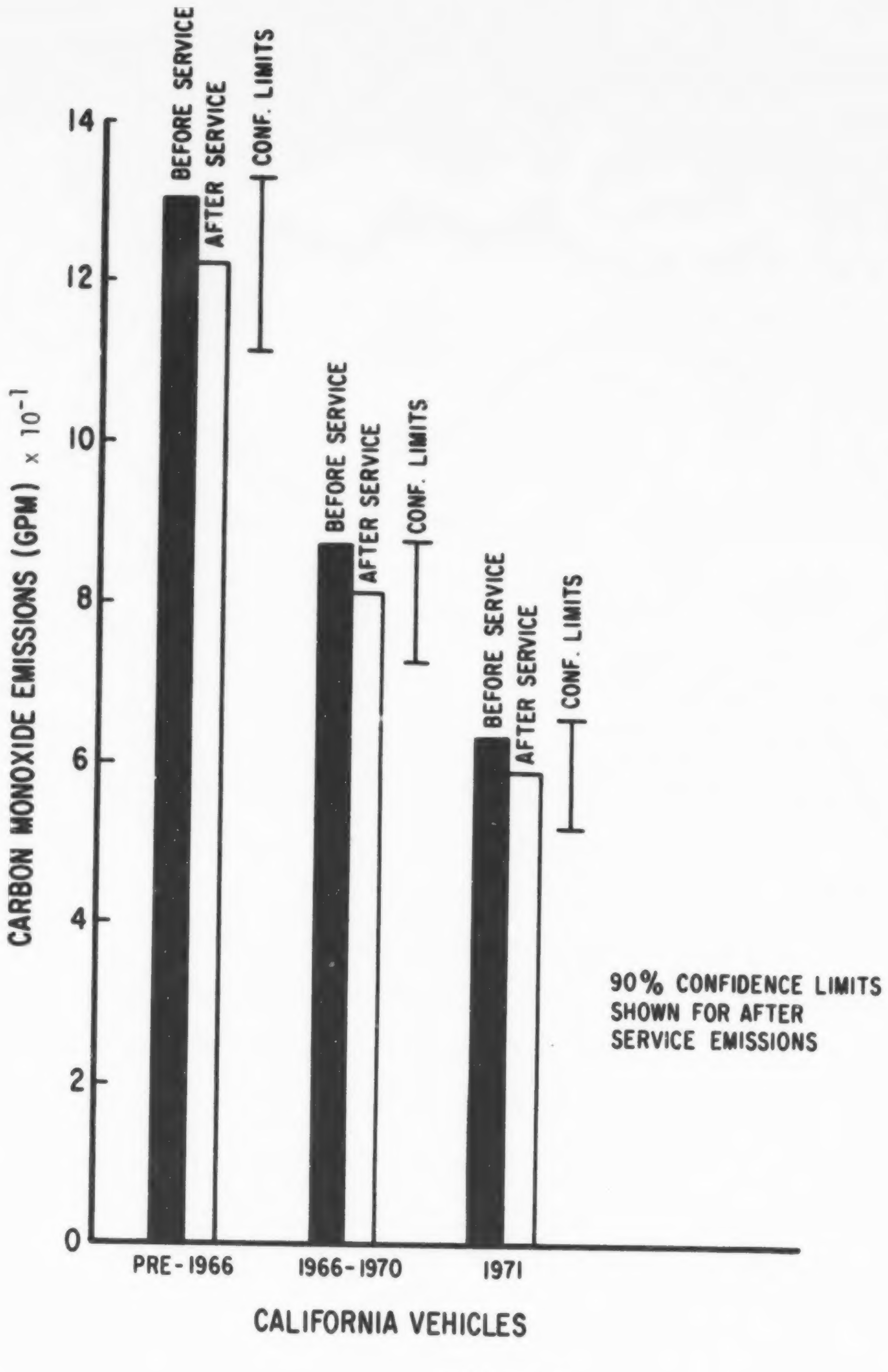


FIGURE 2-5b

FLEET EMISSIONS BEFORE AND AFTER
SERVICE ENGINE PARAMETER INSPECTION

Table 2-16 summarizes the cost elements of the extensive engine parameter inspection. The inspection time estimates are based upon the observed performance of the project personnel during the actual inspection of the test fleet. The total inspection fee includes an additional $1.00 per vehicle to cover State administrative and enforcement cost for the licensed garage system.

TABLE 2-16

ENGINE PARAMETER INSPECTION TEST COST

Subsystem	Inspection Time	Inspection Cost
Idle Adjustments	0.15 hours	$1.50
Secondary Ignition System	0.25 hours	$2.50
Induction System	0.25 hours	$2.50

Total Inspection Fee per Vehicle = $7.50 (includes $1.00 Processing Cost)

The minimum maintenance cost was determined from the extent and frequency of repair that was observed for the test fleet. The labor time required for the repair of each engine parameter was extracted from Chilton's flat rate manual. Table 2-17 lists the repair cost for each parameter that was inspected. Weighting the cost for each parameter by the frequency of malfunction yields the expected cost per vehicle for that parameter.

TABLE 2-17

VEHICLE REPAIR COST FOR ENGINE PARAMETER INSPECTION

Engine Parameter	Repair Cost (Parts and Labor)	Frequency of Occurrence	Expected Cost per Vehicle
A/F Ratio	$ 1.00	40%	$ .40
Timing	$ 1.00	50%	$ .50
Idle RPM	$ 1.00	20%	$ .20
Misfire	$27.00	5%	$1.35
Air Pump	$54.00	3%	$1.62
PCV Valve	$ 2.80	20%	$ .56
Air Cleaner	$ 6.00	20%	$1.20
Heat Riser	$ 2.50	10%	$ .25
Choke Blade	$ 2.50	5%	$ .12
Total Fleet Average Cost			$6.20
Average Cost for Serviced Vehicles Only (90% of Total Fleet)			$7.00

The Chilton's Flat Rate Manual was used to obtain an index for the service cost estimate which was then adjusted to reflect the performance of the test program personnel who actually performed the repairs. Because of their familiarity with the requisite diagnostic and repair functions, the maintenance estimates in Table 2-17 are expected to be considerably below the initial cost that would actually be incurred in a typical service garage. An empirical evaluation of garage effectivenss was conducted to determine the capabilities of the private service industry to diagnose and repair specific engine malfunctions [9]. The results of this study provide a means of adjusting the cost estimates shown in Table 2-17 to account for the frequency and extent of unnecessary repair costs which are likely to occur in practice. It was found that the actual incurred costs for repairs typical of those needed to comply with the inspection program (i.e., idle adjustments plus a component replacement in either the induction or the ignition system) was $22.00. Therefore, during the initial implementation of the inspection program, the annual cost of repair may be up to three times the optimal figures outlined above.

2.3.3 MANDATORY MAINTENANCE

The feasibility of an enforced mandatory tune-up requires the identification of specific engine components and adjustment parameters which have a significant effect upon vehicle emissions and whose malfunctioning can be predicted with a reasonable degree of certainty. The cost-effectiveness of mandatory maintenance is highly sensitive to the identification of the optimal tune-up specifications for each engine component and the reliability of predicting the frequency of malfunction.

The test fleet[10] used to evaluate this strategy was composed of pre-1966 vehicles representative of the domestic vehicle population in California. The repair action included the replacement of the major components in the secondary ignition system (spark plugs, spark plug wires, breaker points, condenser, and distributor rotor), the air cleaner filter, and the PCV valve, and adjustment of the idle parameters (air-fuel ratio, rpm, and timing). The estimated cost for the required parts and labor was $55 per vehicle. A 15% average reduction of exhaust HC emissions and an 11% average reduction of CO emissions were observed following the tuneup of the entire sample fleet. There was no significant change in the fleet mean NOx emissions.

Every vehicle in the test fleet received identical maintenance regardless of the as-received exhaust emissions. Figures 2-6 and 2-7 present the total fleet average emissions after tune-up as a function of the percentage of vehicles receiving maintenance. For this analysis, the vehicles were ranked according to the as-

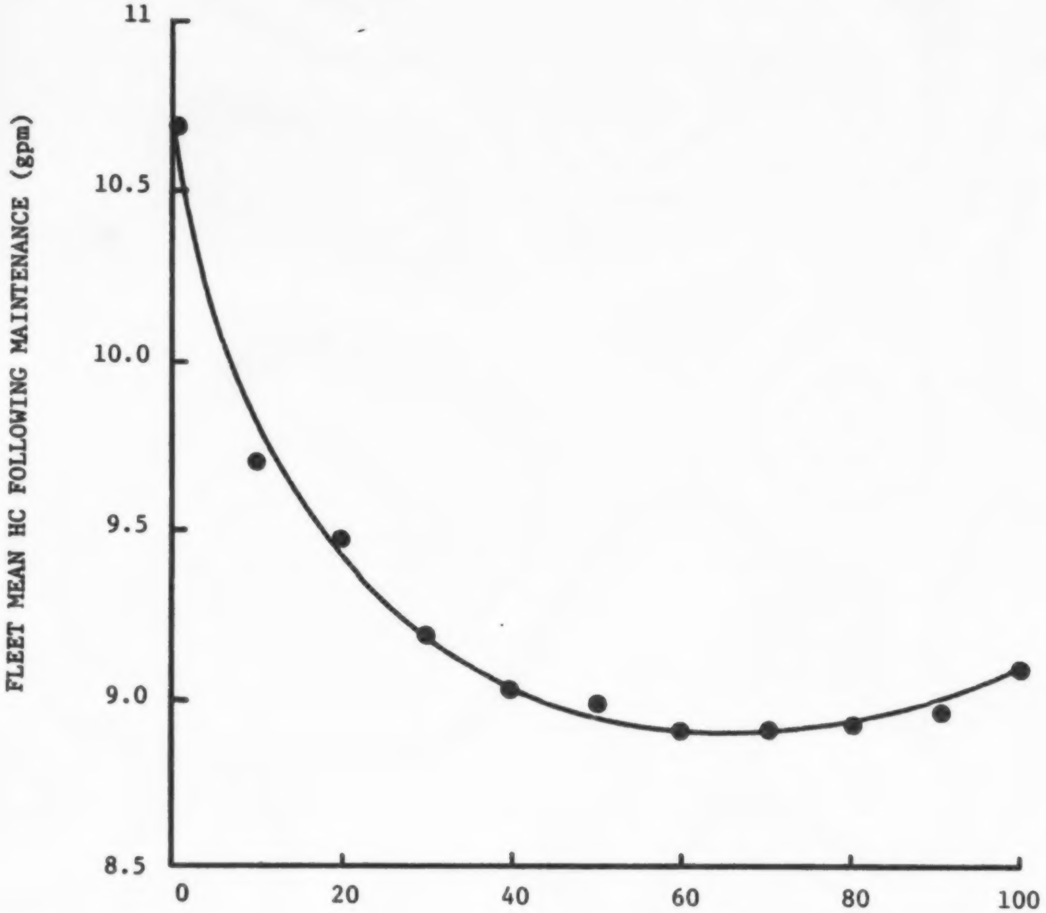


FIGURE 2-6

HYDROCARBON REDUCTION vs. VEHICLE REJECTION RATE

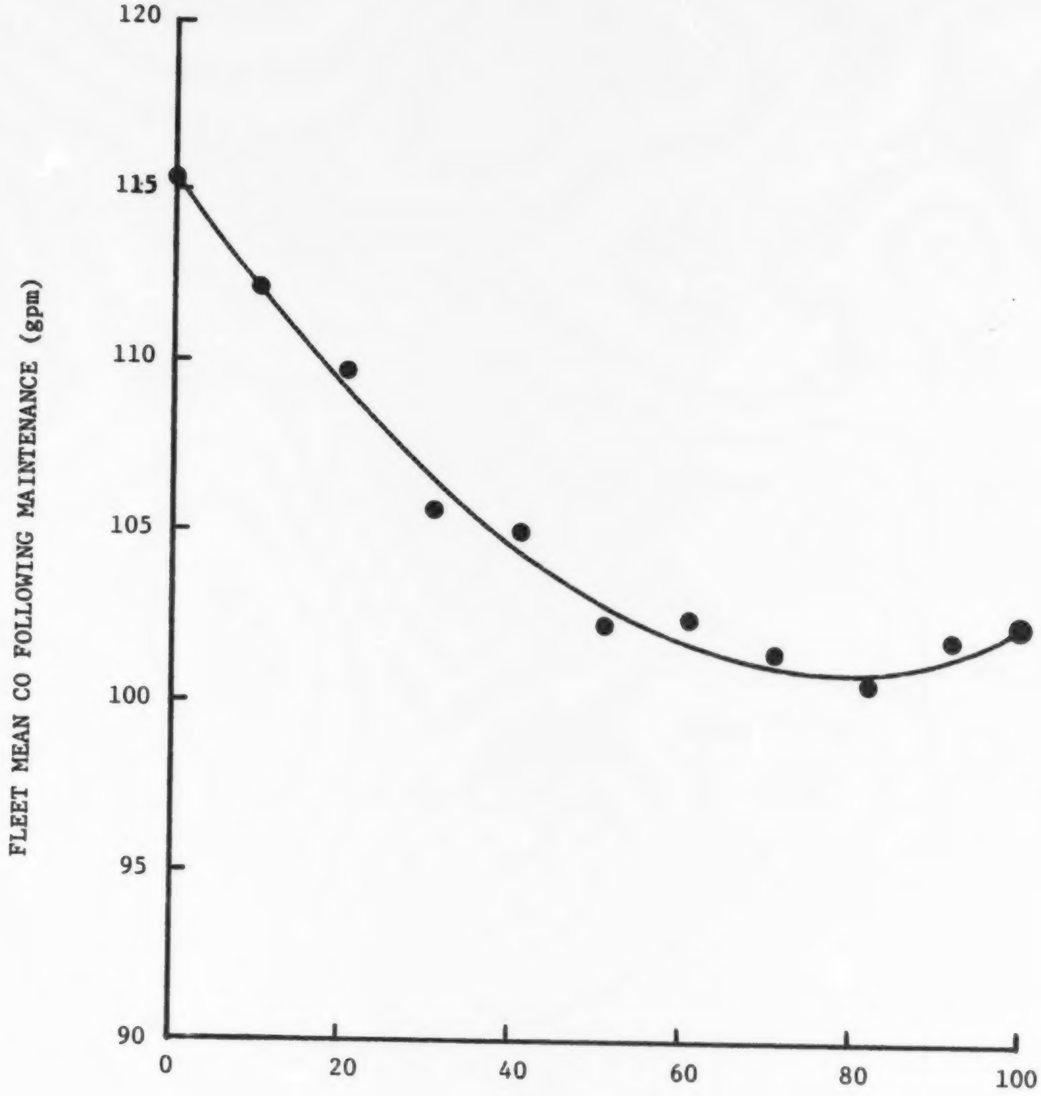


FIGURE 2-7

CARBON MONOXIDE REDUCTION vs. VEHICLE REJECTION RATE received (before tune-up) exhaust emissions; progressively larger fractions of the population were assumed to have been identified for maintenance using an emission test. Each percentile represents the highest emitters comprising that fraction of the test fleet. The analysis demonstrates the potential advantages of the inspection process for selectively identifying those individual vehicles which provide the largest emission reductions.

Figure 2-6 indicates that the maximum leverage for reduction of fleet HC emissions is obtained from the highest emitters composing 20% to 30% of the population. Carbon monoxide reductions improve linearly by increasing the maintenance fraction through 50% of the population The maximum reduction of CO emissions would have resulted from repairing 80% of the vehicles.

Figure 2-8 presents the 90% confidence intervals for the observed reductions of HC and CO exhaust emissions following the maintenance of the entire sample fleet.

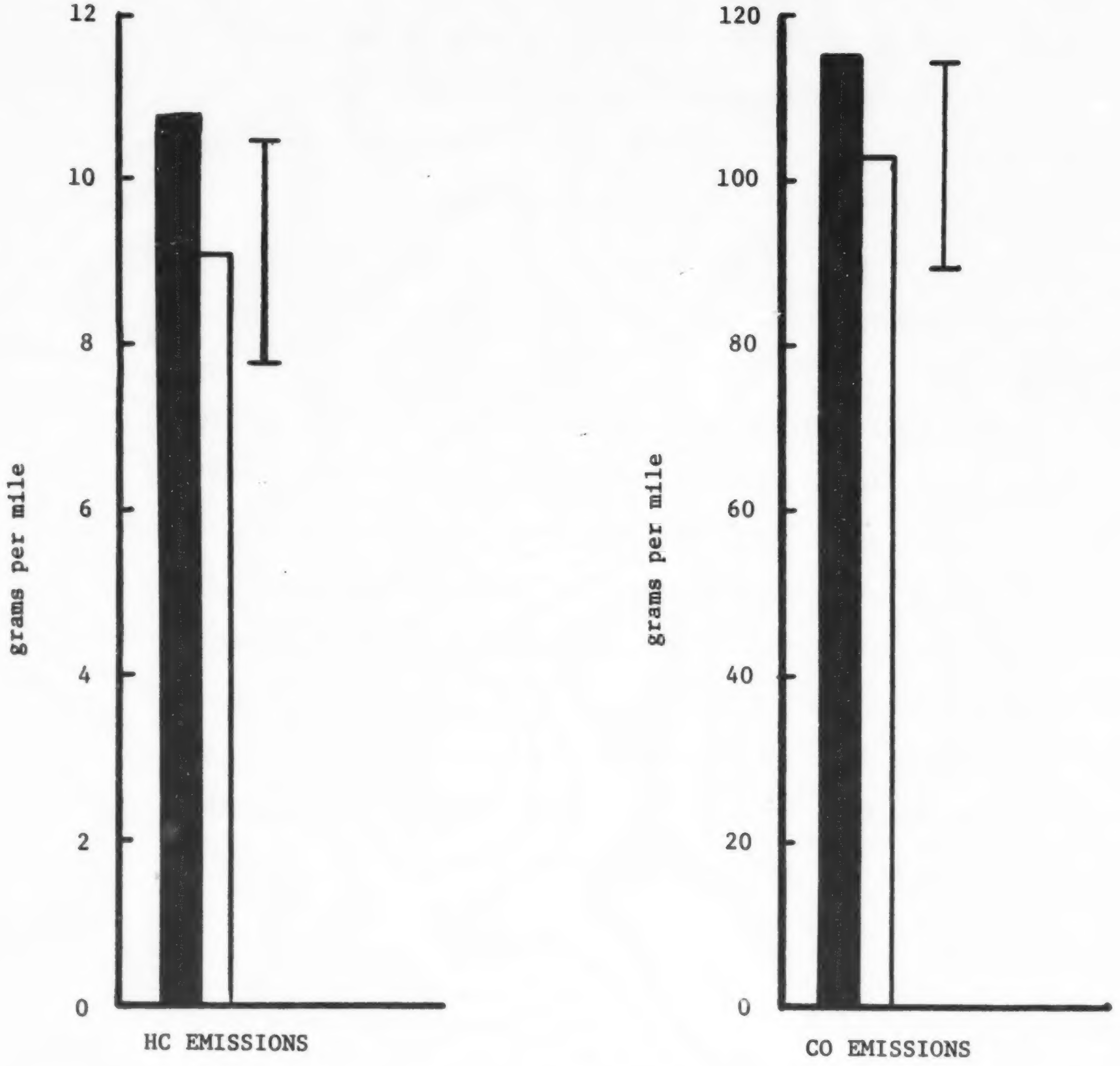


FIGURE 2-8

FLEET EMISSIONS BEFORE AND AFTER SERVICE

2.4 COST-EFFECTIVENESS OF THE INSPECTION/MAINTENANCE STRATEGY

The preceeding section has presented the available data from empirical evaluations of the feasibility, emission reduction effectiveness, and cost of inspection/maintenance strategies. In this section, those data will be employed in evaluating the time-averaged, or steady state, effect on automotive exhaust emissions and the incremental consumer cost likely to result from implementation of such strategies.

The intent of this section is to provide guidance concerning the types of assumptions that are presently considered reasonable in light of the information available, and to exemplify the considerations which are essential for cost-effectiveness projections of an inspection and enforced maintenance program. The empirical base and the assumptions used in the following analysis reflect data which is representative of the nationwide vehicle population. Each of the data sources and each assumption must be individually assessed to determine their applicability for a specific regional analysis.

2.4.1 COST-EFFECTIVENESS CONSIDERATIONS

A comprehensive cost-benefit analysis of the inspection/maintenance strategy should consider the reduction of the total mass of motor vehicle emissions and the total costs and cost savings incurred by developing and maintaining the program. The program costs include the initial investment and operating expenditures which are necessary for the implementation and enforcement of the inspection system; the direct consumer costs attributable to additional vehicle maintenance requirements; and certain implicit costs which should be considered, such as the cost of the inconvenience to the vehicle owner caused by the program's requirements. In addition, there may be ancillary benefits such as reduced fuel consumption and the effects of preventative maintenance which should be considered.

Many of these considerations cannot be evaluated at this time because the supporting data required to do so is currently insufficient. The evaluation of those factors which are considered in this section also relies upon specific simplifying assumptions. The most significant assumptions concern the estimates of the emission reductions which can be achieved by the implementation of an inspection program.

The initial fleet emission reductions presented in Section 2.3 indicate the maximum reductions that can be anticipated for enforced maintenance programs, whereas something less effective must be expected. It is known that vehicle emissions will change, perhaps quite substantially, during the elapsed time between maintenance events. The true impact upon air quality cannot be determined without some knowledge of both the extent of the deterioration of emission control, and the rate of deterioration as a function of time.

Figure 2-9 shows two possible emission-time traces for a hypothetical motor vehicle. At time t_0, the vehicle receives maintenance and the emission level is reduced from point F to point E. The two curves "a" and "b" reflect the emission level as a function of elapsed time attributed to the deterioration of emission control. The extent

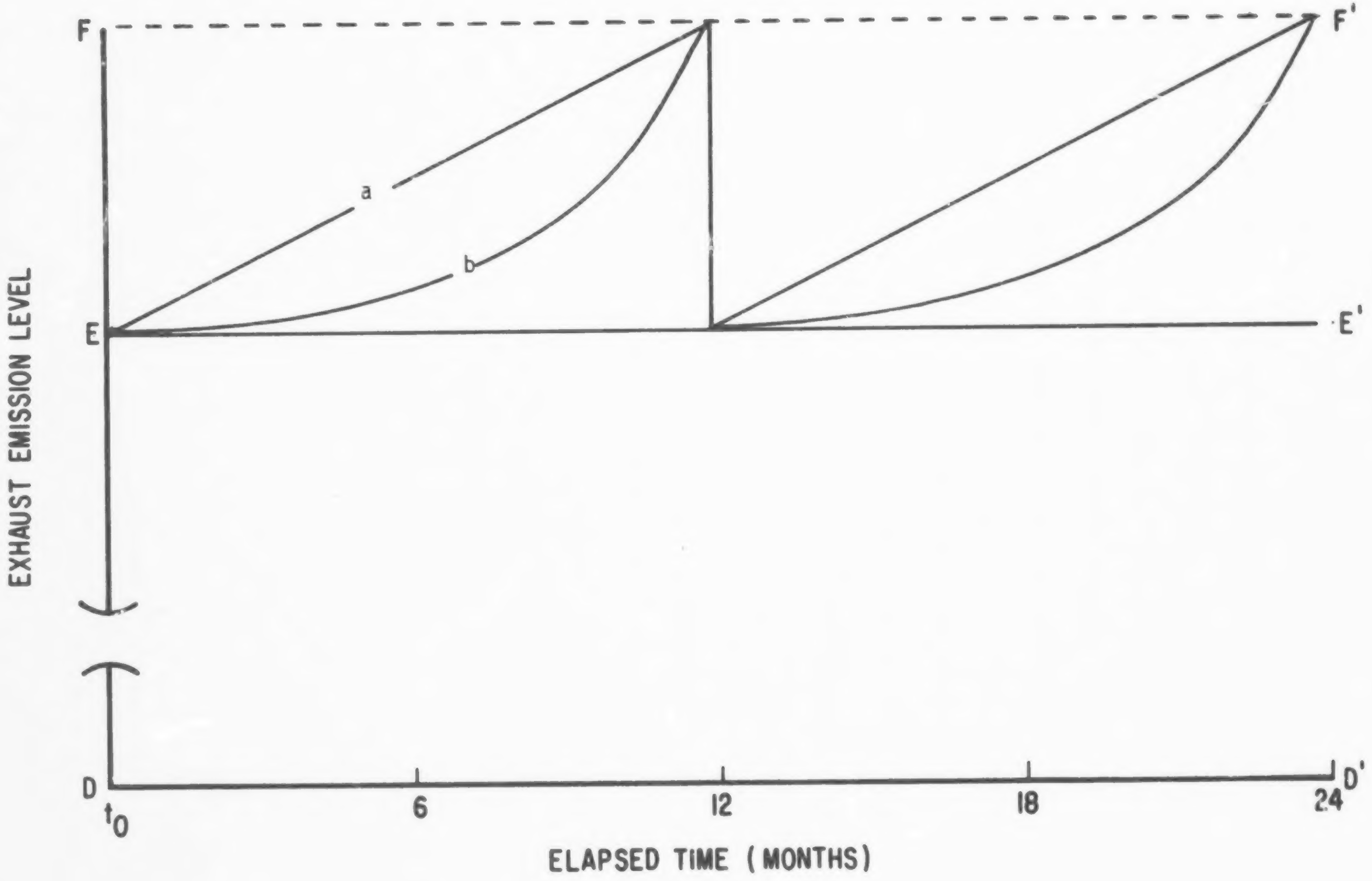


FIGURE 2-9

REPRESENTATIVE EMISSION-TIME HISTORY FOLLOWING TUNE-UP of deterioration is assumed to be equivalent after 12 months, at which time the emissions reach point F and the vehicle again receives maintenance. The effectiveness of this maintenance schedule is reflected by the fraction of the total area (between FF' and DD') which is enclosed by the line FF' and the appropriate deterioration curve. It is clear, therefore, that the effectiveness of an enforced maintenance program is highly dependent on the shape of the deterioration curve, as well as the extent of deterioration between the maintenance events. Lacking any information to define the rate of deterioration as a function of time, the calculations presented in the ensuing analysis will assume it to be linear. The data used to quantify the deterioration rate are described in Section 2.4.2.

An additional consideration when estimating the impact of motor vehicle emissions upon air quality is the relative contribution of the three sources of automotive hydrocarbon emissions. The previous discussions have considered only the reduction of exhaust gas HC emissions; however, additional emissions must be attributed to engine blowby (crankcase emissions) and the evaporation of raw fuel. It is assumed for recent model years that the crankcase emissions have been essentially eliminated. However, evaporative emission control was not initiated until the 1971 model year vehicles, and it cannot be assumed that fuel evaporation will be completely controlled within the 1975 to 1980 time frame. Accordingly, this emission source will become a substantially larger component of total automotive HC emissions as increasingly stringent Federal exhaust emission standards become effective.

Projected baselines of total light duty vehicle hydrocarbon and carbon monoxide emissions through the 1985 calendar year are presented in Figures 2-10 and 2-11 respectively. The baselines were calculated on a nationwide basis using the approach and assumptions described in the "Regulations for the Preparation, Adoption, and Submittal of Implementation Plans"[11]; emissions from heavy duty vehicles have been excluded, and an annual linear growth rate of 5% in total light duty vehicle miles travelled has been used. Each curve has been normalized relative to total light duty vehicle emissions in 1967, the year prior to the implementation of Federal emission standards.

For illustrative purposes, the maximum reduction of exhaust emissions observed in the pilot studies (i.e., 25% for HC and 19% for CO) are used to demonstrate the impact of an inspection/maintenance strategy assuming the program is implemented in 1974.

The relative reduction of total HC emissions progressively decreases as the exhaust emissions become less significant relative to the contribution of evaporative emissions. The relative reduction of carbon monoxide emissions remains constant as the exhaust gas is the only source of automotive CO emissions.

The effectiveness and feasibility of inspection procedures for the detection of malfunctions of either NOx control systems or evaporative HC emission control systems has not been evaluated since these control systems were not required in order to comply with Federal emissions standards until the 1971 model year for evaporative control, and the 1973 model year for NOx control.

The relative contribution of exhaust HC emissions and evaporative emissions is determined by the vehicle model year distribution within

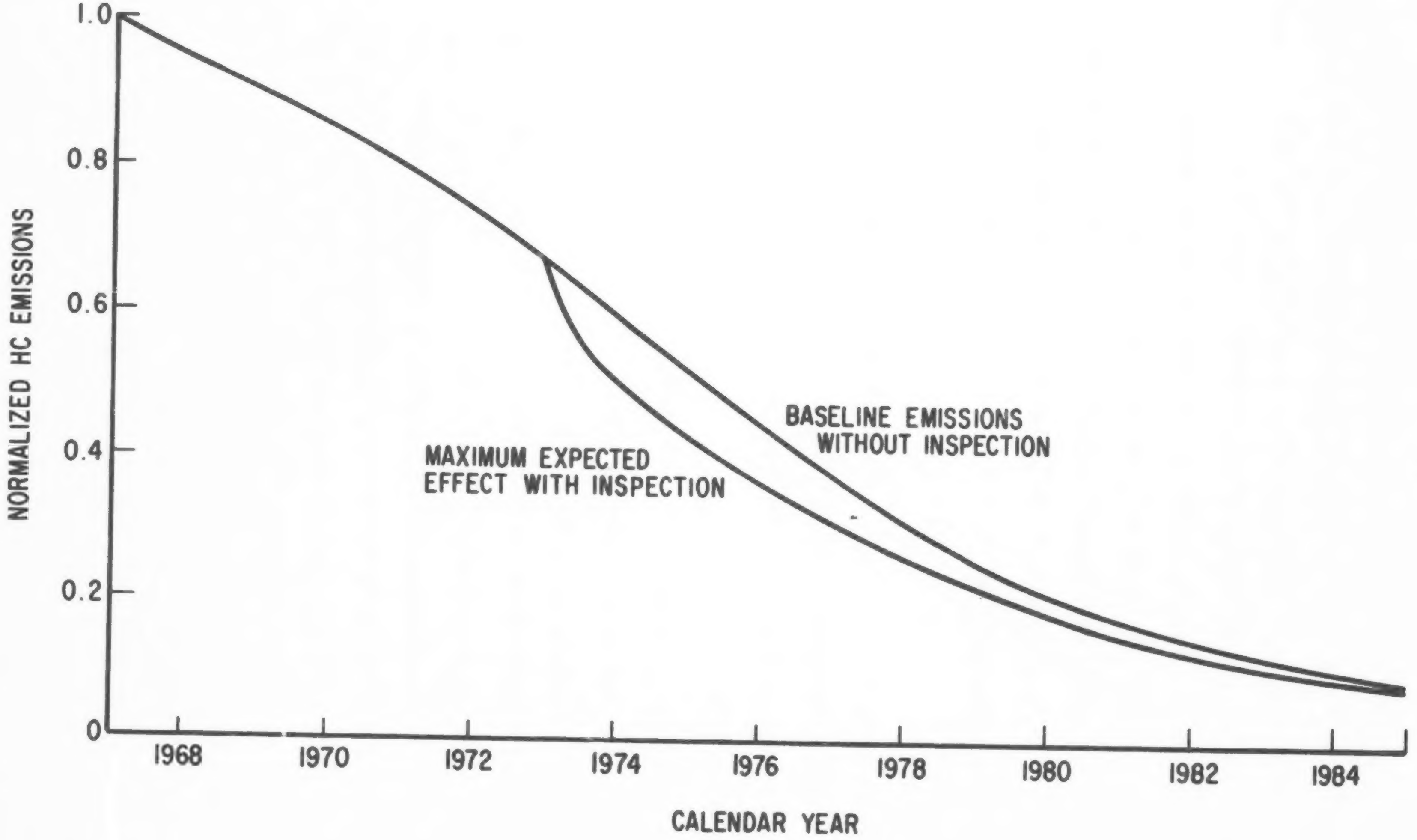


FIGURE 2-10

NORMALIZED HYDROCARBON EMISSIONS TOTAL LIGHT DUTY VEHICLE POPULATION

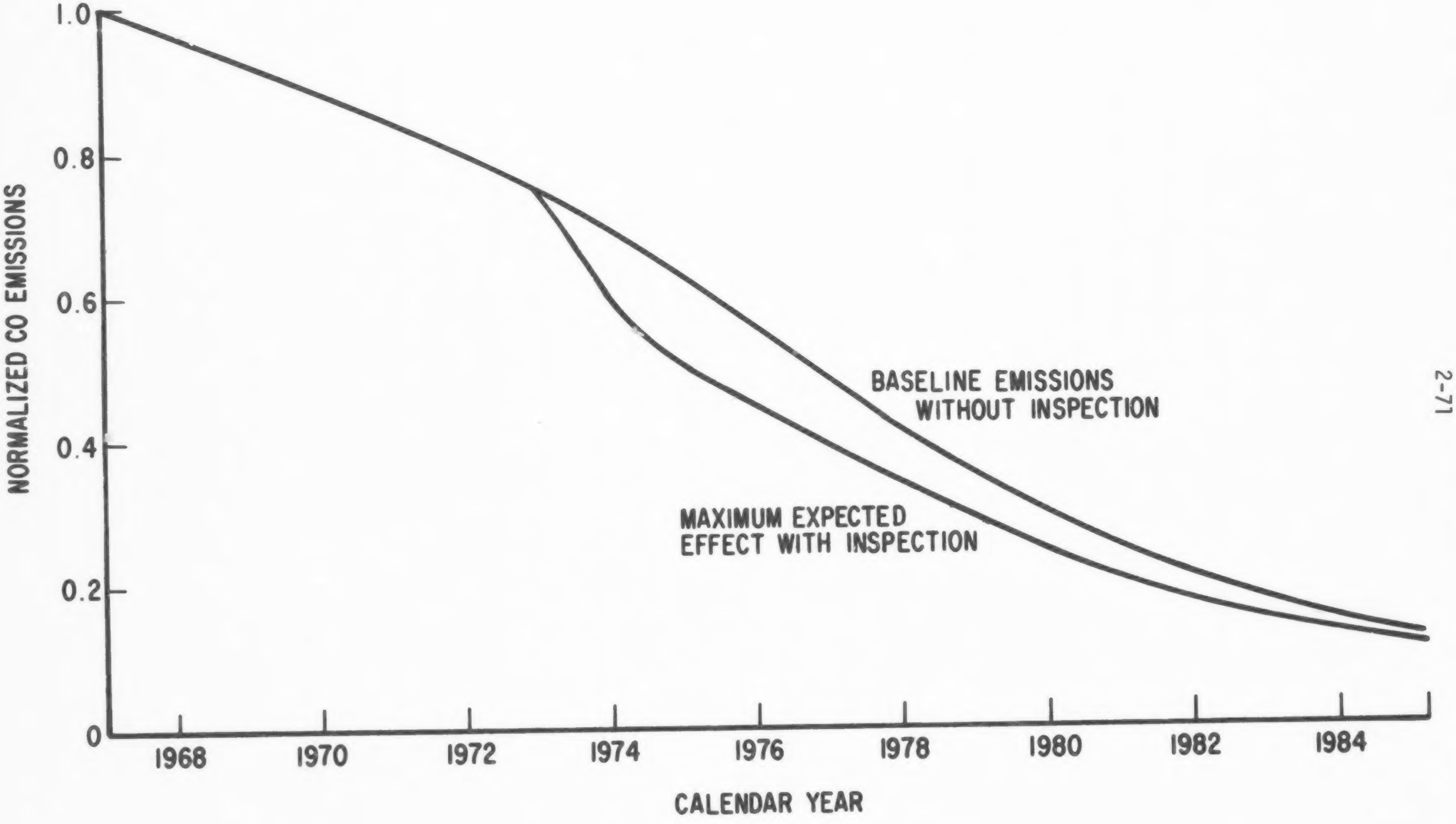


FIGURE 2-11

NORMALIZED CARBON MONOXIDE EMISSIONS TOTAL LIGHT DUTY VEHICLE POPULATION any specific region. To eliminate this regional sensitivity from the cost-effectiveness analysis, the analysis will consider the exhaust emission reductions only. This is also advantageous for maintaining continuity between the time-averaged effectiveness and the initial emission reductions presented in Section 2.3.

2.4.2 ANALYTICAL APPROACH

A cost-effectiveness analysis has been made to determine the expected impact of the inspection/maintenance strategy between 1975 and 1980. The economic estimates are quantified in terms of the incremental annual cost per vehicle discounted to the present (1972 dollars). The cost attributes include the incremental cost for vehicle repair and the initial investment and operating expenditures necessary for the implementation and administration of the inspection program. To ensure the generality of the analysis, the cost estimates are made for the inspection lane configuration (see Section 2.3.1). Because the lane system is designed to operate at maximum capacity, thereby achieveing optimum efficiency, its cost per vehicle inspection is less sensitive to regional variations in the size and density of the vehicle population than that for a licensed private garage system.

The data sources which are used to support the cost-effectiveness estimates are summarized in Table 2-18. The results of the Short Cycle Study provide an estimate of the current baseline emission level as reflected by the total fleet mean before service and an estimate of the minimum potential emission level as reflected by the total fleet mean after service. The data are presented for the pooled mean of all four test fleets. The actual repair costs incurred during the Short Cycle

TABLE 2-18

DATA SUPPORTING THE CALCULATION OF THE TIME DETERIORATION RATE FOR VEHICLE EXHAUST EMISSIONS

------------ Pooled Emission Results of the Short Cycle Study ----------

	Exhaust Emissions	
	HC (gpm)	CO (gpm)
Total Composite Fleet		
As Received (gpm)	7.98	94.32
After Service (gpm)	5.98	76.12
Reduction (gpm)	2.00	18.20
Serviced Vehicles		
As Received (gpm)	10.46	114.98
After Service (gpm)	6.53	78.61
Reduction (gpm)	3.94	36.37

Average Maintenance Cost Per Serviced Vehicle = $28.52

-------------------Maintenance Survey Data *----------------------------

Maintenance Interval Limits	Percentage of Vehicle Population	Average Maintenance Interval
Greater than 0 months	100	10.25 Months
Greater than 6 months	81	11.63 Months
Greater than 12 months	30	22.12 Months

Average Maintenance Cost per Service Event = $36.86

* Champion Spark Plug Company (see reference 13)

Study are used to estimate the service cost for emission related maintenance.

The results of a recently completed survey of owner maintenance habits by the Champion Spark Plug Company[13] provide information concerning the frequency of maintenance and the average repair costs per service event for current voluntary maintenance.

The cost-effectiveness calculations set forth in this section present an estimate of the rate of emission control deterioration based upon the elapsed time since the last voluntary maintenance event prior to the "as-received" emission test for the Short Cycle Study fleet. The deterioration factor is then used to calculated the baseline emission level assuming the implementation of an enforced 12 month inspection interval and a 6 month inspection interval. The incremental maintenance cost necessary to achieve compliance with the inspection program is estimated for that segment of the population currently receiving maintenance less frequently than the inspection frequency, and the cost is distributed over the total population.

The cost-effectiveness calculations rely upon the following explicit assumptions:

- The present emission baseline without enforced maintenance is equivalent to the "as-received" pooled mean emission level of the four test fleets evaluated in the Short Cycle Study. The minimum potential emission level which can be achieved through an emission-related maintenance program is reflected by the "after service" emission level observed in the Short Cycle Study.

- The frequency of maintenance and repair costs observed in the Champion Survey are representative of the present nationwide population mix by model year and manufacturer.
- The average time since the last maintenance event for any randomly selected sample of vehicles will be one-half the average maintenance interval for the population.
- The existing levels of voluntary maintenance will be conserved following the implementation of an enforced inspection program.
- The deterioration is linear and remains constant as a function of vehicle age.
- The emission reductions will be equivalent for all vehicles receiving maintenance whether the maintenance is voluntary or in response to the failure of an inspection standard.
- The relative behavior of emission levels of future vehicle populations will exhibit the same dynamic effects due to deterioration and control system maintenance as the vehicle distribution presently in use.

2.4.3 TIME-AVERAGED EFFECTIVENESS

The dynamic effect of emission control deterioration between maintenance events for individual vehicles produces a steady state, or constant, emission baseline for any given level of maintenance of the total vehicle population. The deterioration rate is fixed by the design, and the inherent stability, of the emission control system. The maintenance interval, however, can be altered according to the enforcement policy of a vehicle inspection program.

In order to calculate the steady state emission baseline following the implementation of an inspection program, an estimate must be made to quantify the deterioration parameter. The Champion Survey indicates that the average maintenance interval for emission related systems of the current in-use vehicle population is 10.25 months. The results of the survey were statistically weighted to reflect the nationwide vehicle distribution by age, manufacturer, and engine size. It assumed that the composite results obtained by pooling the emission measurements for the four test fleets used in the Short Cycle Study are also representive of the nationwide population mix.

On the premise that the emission test fleets are truly a valid random sample of the population, the average maintenance interval for these vehicles can be assumed to be 10.25 months. Accordingly, the average time elapsed between the last voluntary maintenance event and the "as-received" emission test would be 5.125 months. If the average emission level immediately following the last maintenance event were know, an estimate of the deterioration rate could be calculated in terms of grams per mile per month.

Lacking this information, three deterioration rates will be used to provide a parametric analysis of the cost-effectiveness. The independent rates of deterioration are based on assumptions regarding the effectiveness of conventional voluntary maintenance relative to the effectiveness of emission related maintenance observed in the Short Cycle Study (see Figure 2-12). As can be seen, the maximum deterioration rate is implied if conventional maintenance and emission-related maintenance are found to be equally effective. Conversely, as the effectiveness of conventional maintenance approaches zero, the deterioration rate must also approach zero. The deterioration factors for HC and CO corresponding to the three levels of relative effectiveness of conventional maintenance are shown in Table 2-19.

TABLE 2-19

------------ Calculated Deterioration Factors --------------------

Relative Effectiveness Assumed for Conventional Maintenance	Deterioration Factor HC	CO
0.50 (Low Deterioration)	0.195 gpm/month	1.78 gpm month
0.75 (Median Deterioration)	0.290 gpm/month	2.56 gpm/month
1.00 (High Deterioration)	0.390 gpm/month	3.55 gpm/month

Using each of the three deterioration factors, the emission baseline is calculated for both a twelve month inspection interval, and a six month inspection interval. In each case, the vehicle population is partitioned into two groups; one group being composed of vehicles currently maintained more frequently than the inspection interval, and the other group composed of the vehicles currently maintained less frequently than the inspection interval. Conservation of maintenance is assumed for the population segment with the higher frequency of maintenance, and the time averaged

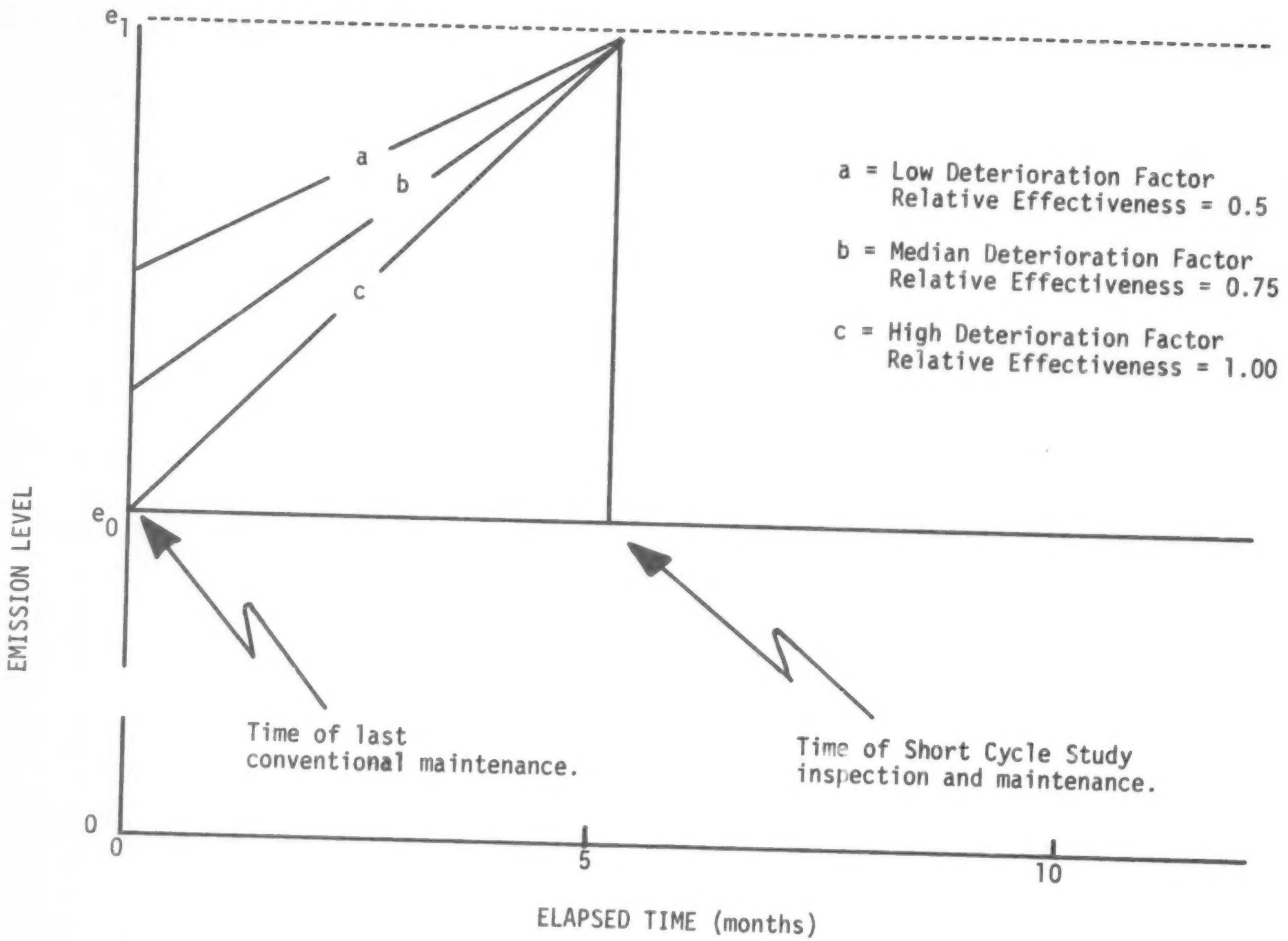

e_1
e_0
0
EMISSION LEVEL
a
b
c
a = Low Deterioration Factor Relative Effectiveness = 0.5
b = Median Deterioration Factor Relative Effectiveness = 0.75
c = High Deterioration Factor Relative Effectiveness = 1.00
Time of last conventional maintenance.
Time of Short Cycle Study inspection and maintenance.
0
5
10
ELAPSED TIME (months)

FIGURE 2-12

ASSUMPTIONS RELEVANT TO DETERIORATION CALCULATION emission level is calculated on the basis of the elapsed time between maintenance events.

It is asssumed that the enforcement of the inspection program will require the remaining vehicles to receive maintenance as frequently as the inspection interval. The time averaged emission level is calculated for these vehicles, and the weighted sum of the two segments of the population represents the steady state emission baseline for the appropriate inspection interval. The calculations are defined as follows:

$$Pp\ [Eo + (DF \times MIp \times \tfrac{1}{2})] = Ep$$

$$Pf\ [Eo + (DF \times II \times 1/2)] = Ef$$

$$(Pp \times Ep) + (Pf \times Ef) = E_{ti}$$

$$ER = (Eni - Eti)/Eni$$

where: Pp = fraction of vehicle population currently serviced more frequently than the inspection interval.

Pf = fraction of vehicle population currently serviced less frequently than the inspection interval.

Eo = minimum emission level immediately following maintenance.

DF = deterioration factor in terms of grams per mile per month.

MIp= current average maintenance interval of vehicles passing the inspection test.

Ep = time averaged emission level of vehicles passing inspection test.

II = inspection interval

Ef = time averaged emission level of vehicles failing inspection test.

1/2: constant to determine average emission level between maintenance events assuming a linear deterioration rate.

Eti= emission baseline for total vehicle population following the implementation of an inspection/maintenance program.

Eni= emission baseline for total vehicle population prior to the implementation of an inspection/maintenance program.

ER = emission reduction relative to the initial emission level (Eni).

The effectiveness of a twelve month and a six month inspection interval corresponding to each of the three deterioration factors are shown in Table 2-20. Only the reduction of HC and CO emissions were calculated because the results of the maintenance programs have not demonstrated a statistically significant change in the emissions of nitrogen oxides.

TABLE 2-20

TIME AVERAGED EFFECTIVNESS OF ENFORCED INSPECTION/MAINTENANCE PROGRAMS

Inspection Interval	Annual Vehicle Rejection Rate (% of total fleet)	Deterioration Factor	Exhaust Emission Reduction HC	CO
12 months	30%	High DF	7.4%	5.72%
		Median DF	11.9%	9.5%
		Low DF	16.7%	12.5%
6 months	81%	High DF	11.2%	8.6%
		Median DF	14.7%	11.6%
		Low DF	18.1%	13.9%

2.4.4 ECONOMIC ESTIMATES

The incremental costs which can be attributed to the enforcement of an inspection program include the capital investment requirement and the annual operating cost of the inspection program, and the additional economic burden placed on the vehicle owner as a result of the additional maintenance required to comply with the test standards. To provide the widest range of applicability, the inspection costs are estimated for the publicly operated inspection lane configuration.

The cost estimates presented in Section 2.2 indicate that an annual cost of $1.22 per vehicle inspection would be adequate to account for the administrative expense of a dynamic mode emission inspection utilized in a high throughput lane confirguration. An assumed inspection fee of $1.50 per vehicle inspection is used in the following calculations to ensure the coverage of any additional hidden cost factors. The incremental maintenance costs are based on the higher frequency of maintenance imposed by the inspection program. There is no attempt to account for a cost increase per maintenance event. It is assumed that the improvement in maintenance procedures to achieve the maximum reductions does not require the use of repair techniques which are any more comprehensive than those generally recommended by the vehicle manufacturer.

The methodology used to calculate the incremental maintenance cost is similar to the emission baseline calculation. Conservation of existing maintenance is assumed for that portion of the vehicle population which currently receives maintenance more frequently than would be required by the inspection policy. Those vehicles which receive maintenance less frequently, receive the incremental cost burden as the maintenance interval is reduced to comply with the inspection test. The cost burden imposed on this fraction of vehicles is then distributed over the entire population such that the cost figure per vehicle is comparable to economic estimates for other emission control strategies.

The estimated cost for existing maintenance is provided by the Champion Survey data which indicates an average of $36.86 per service event. The cost for incremental emission related maintenance is assumed to be $28.52 per service event. This figure reflects the pooled average repair cost per serviced vehicle in the Short Cycle Study. The annual rejection rate will determine the number of additional tests required for the after service compliance test. The added cost for the compliance testing is assumed to be included in a single inspection fee for all vehicles subject to the enforcement program. The cost calculation is defined as follows:

$$Cm = Pf\ (II \times 1/12 \times Cem) - Pf\ (MIf \times 1/12 \times Ccm)$$

$$CI = Cvt\ [(II \times 1/12) + Pf\ ]$$

where:

Cm = the incremental annual cost per vehicle for additional maintenance requirements.

C_{em}= cost per service event for emission related maintenance.

Ccm= cost per service event for present conventional maintenance.

Pf = fraction of vehicle population currently serviced less frequently than the inspection interval.

II = inspection interval in months.

MIf= current average maintenance interval of vehicles failing inspection test.

CI = annual inspection cost per vehicle.

Cvt= annual inspection cost per vehicle test.

The incremental cost estimates for a twelve month and a six month inspection program are summarized in Table 2-21.

TABLE 2-21

INCREMENTAL COST ATTRIBUTES FOR AN ENFORCED INSPECTION PROGRAM

	Inspection Interval	
	12 months	6 months
Inspection Cost per Vehicle	$2.00	$4.22
Incremental Maintenance Cost per Vehicle	$2.56	$15.40
Total Average Cost per Vehicle	$4.56	$19.66
Total Average Annual Cost per Vehicle for 1975-1980 (present worth)	$3.97	$17.08

2.4.5 COST-EFFECTIVENESS SUMMARY

The cost and effectiveness results estimated by this analysis are summarized in Table 2-22. Also shown are values of a cost-effectiveness index derived by equally weighting the percentage reductions for all three pollutants and dividing the weighted reduction by the program cost. Because the same basic assumptions apply to both HC and CO emission reductions, the relative values of the cost-effectiveness index for the various choices of inspection interval and deterioration factor are independent of the pollutant weighting factors chosen; therefore, equal weighting was chosen for simplicity. For the entire range of deterioration factors considered in the analysis, a twelve-month inspection interval is seen to be less effective, but more cost-effective, than a six-month interval. That is, the additional reductions obtained by decreasing the inspection interval from twelve to six months are more costly than the reductions first obtained by implementing a twelve-month interval program. However, as is shown by Table 2-23, the relative effectiveness and cost-effectiveness of twelve and six-month inspection intervals vary significantly with the assumed deterioration factor.

Thus, a principle parameter in the cost-effectiveness analysis is the effectiveness of current conventional maintenance relative to that which may be performed in response to an enforced inspection/maintenance program; for this relative effectiveness provides the basis for quantifying the deterioration factor. If it is assumed that current maintenance is effectively performed (a relative effectiveness factor of 1.00), the results obtainable through tuning up test fleets indicate that the rate of

TABLE 2-22

COST-EFFECTIVENESS OF INSPECTION/MAINTENANCE STRATEGY

FOR

1975 THROUGH 1980

Inspection Interval	Incremental Cost	Deterioration Factor	Reduction of Exhaust Emissions HC	CO	NOx	Weighted Reduction	Cost-Effectiveness Index
12 months	$ 4.00	High DF	7%	6%	0	4.4	1.1
		Median DF	12%	10%	0	7.1	1.8
		Low DF	17%	12%	0	9.7	2.4
6 months	$17.00	High DF	11%	9%	0	6.6	0.4
		Median DF	15%	12%	0	8.8	0.5
		Low DF	18%	14%	0	10.7	0.6

TABLE 2-23

SENSITIVITY OF COST-EFFECTIVENESS PARAMETERS

Assumed Relative Effectivenss Index for Conventional Maintenance	1.00	0.75	0.50
Wtd. Effect.[+] 12 mo. II / Wtd. Effect. 6 mo. II	0.66	0.81	0.91
CEI[*] 12 mo. II / CEI 6 mo. II	2.78	3.45	3.85

[+] Weighted emission reduction for an inspection/maintenance program requiring a 12 month inspection interval.

[*] Cost-effectiveness index for an inspection/maintenance program requiring a 12 month inspection interval.

deterioration as a function of time is high. In that case, a short inspection interval would be necessary to keep vehicle emissions at a minimum, but the present performance of the maintenance industry would appear adequate to achieve the expected reductions.

On the other hand, if the emission reductions typically achieved through conventional maintenance are small (a relative effectiveness factor of 0.50), the empirical test fleet data imply a low rate of deterioration. In that event, only minimal additional emission reductions would be obtained by shortening the inspection interval. However, substantial improvements in the diagnostic and repair performance of the maintenance industry would be necessary to ensure the effectiveness of the inspection/maintenance program.

There is a limited amount of information in the literature which provides some guidance as to the relative effectiveness of current conventional maintenance practices. The garage effectiveness study[5] discussed in Section 2.3.2 indicates that the diagnostic and repair performance of the current maintenance industry achieves reductions between 60% and 80% of the maximum reductions that could be achieved through emission-related maintenance. On the other hand, an earlier study[14] indicated that conventional tune-up practices achieve reductions of less than one-half the magnitudes obtained when optimal emission tune-ups were performed. However, in this latter study, the optimal tune-up procedures used as a reference included adjusting the vehicles to the minimum idle CO levels achieveable without misfire, rather than to manufacturer's specifications.

Based upon the available data, it appears that an intermediate effectiveness factor of 0.75 is a reasonable assumption to reflect the relative effectiveness of current voluntary maintenance in reducing emissions. Accordingly, the expected average effectiveness over time of an annual inspection/maintenance program would be as follows:

HC exhaust emission reduction-------12%
CO exhaust emission reduction-------10%
NOx exhaust emission reduction-------no significant change

2.5 CORRELATION ANALYSIS

In the context of the need for transportation control measures, the single purpose of a periodic inspection program is to achieve reductions in the average rate of vehicular emissions during operation. Since the Federal Test Procedure is the single standard of measure for defining typical urban emission levels, an effective inspection test should pass and fail individual vehicles in a manner similar to the way in which the same vehicles would pass or fail the FTP. Testing any two vehicles, the inspection test should preferentially identify the highest emitting vehicle to receive maintenance. In addition, compliance with the inspection test failure criteria following corrective maintenance must, in fact, represent a significant reduction of true mass emission levels as measured by the FTP if the program is to accomplish its goal.

There are two basic methods for evaluating the potential effectiveness of inspection procedures in fulfilling the objectives outlined above. The first approach is to directly measure the change in the average emission levels for a large test fleet which has been subjected to the appropriate inspection and maintenance procedures. The results of studies using this type of approach were presented in Section 2.3.

Alternatively, a statistical analysis can be performed to evaluate the correlation between the inspection emission measurement and the actual vehicular emission levels as measured by FTP. Conceptually, this type of approach is an attempt to quantify the information content of the inspection test procedure. The degree of correlation indicates the accuracy with which the inspection test is monitoring true emission rates, and provides a measure of the assurance that compliance with the inspection will actually result in emission reductions.

The data used for this analysis were obtained as a parallel task in the Short Cycle Study. In each of the four test fleets, independent emission measurements were made using the FTP and a number of alternative hot start test procedures and individual test modes. A regression analysis was performed, and the degree of correlation between the FTP and alternative short test procedures was determined using the pooled test data from each fleet. Hereafter, the term short test will refer to any composite test procedure, or to any individual test modes, which are considered feasible alternatives for an inspection test procedure.

2.5.1 DESCRIPTION OF TEST PROCEDURES EVALUATED

A wide range of composite test procedures and individual test modes were evaluated in order to investigate the full spectrum of feasible alternatives which have been proposed for use in an emission inspection program. The intent of the analysis was to identify the emission test characteristics which have the most substantial effect on the correlation with the Federal Test Procedure. Accordingly, the analysis evaluated composite transient mode tests, a number of constant velocity cruise modes, and the idle mode. Both mass emission measurements and volumetric (concentration) emission measurements were also evaluated. The basic characteristics of each test procedure are summarized below.

1972 Federal Test Procedure[1] - This is the standard of measure for defining vehicular emission levels during typical urban driving patterns. The FTP is a cold start test (the vehicle remains inoperative for a minimum of twelve hours prior to initiating the test) which utilizes a 23-minute non-repetitive transient mode driving cycle, and provides a CVS mass emission measurement of total hydrocarbons, carbon monoxide, and total oxides of nitrogen.

Federal Short Cycle Test - The Federal Short Cycle is a composite transient mode cycle composed of nine operating modes including accelerations, declerations, cruise modes, and idle operation. The duration of the test cycle is 125 seconds. Mass emission rates of total hydrocarbons, carbon monoxide, and total oxides of nitrogen are measured. The dynamometer load factors are set according to the weight class of the individual vehicles.

Hot Seven Mode Test - Two repetitions of the standard Seven Mode test cycle (see Figure 2-1, Section 2.2.1) were made from a hot start. Both mass emission and volumetric emission measurements were made simultaneously. The volumetric emission rates provide a measure of total hydrocarbons as n-hexane (using NDIR), carbon monoxide, and oxides of nitrogen as NO (using NDIR). The duration of each Seven Mode Cycle is 136 seconds. The power absorption unit on the dynamometer was uniformly set for 10 hp at 50 mph for every test vehicle.

Steady State Test Modes - Mass emission rates and volumetric emission rates were measured at constant cruise speeds of 10, 20, 30, 40, 50, and 60 mph. Mass and volumetric measurements were made at zero mph with the transmission in neutral; this was defined as the idle mode measurement. The power absorption unit was set to correspond to the weight class of the individual test vehicle. Hereafter, these cruise modes will be referred to as the steady state modes to differentiate them from the Key Mode cruise modes which use a higher loading factor.

Key Mode Test - Mass emission rates and volumetric emission rates were measured during the idle mode and each of the two cruise modes which comprise the Key Mode[2] vehicle operating cycle. The power absorption unit was set for 30 hp at 50 mph. In comparison, the road load setting for a 3000 pound vehicle using the Federal Test Procedure is approximately 10 hp at 50 mph.

An emission measurement was made for every vehicle in the Short Cycle Study both before and after service using each of the test procedures described above.

2.5.2 DESCRIPTION OF CORRELATION ANALYSIS

A regression analysis of the data obtained from the Short Cycle Study was performed to formulate a functional relationship between the various short tests and the Federal Test Procedure using the method of least squares.[7] This regression equation provides a means of predicting the true mass emission (FTP) rate as a function of the short test emission measurement. The simple regression equation is of the general form:

$$\hat{Y} = a + bX$$

where $\hat{Y}$ (the dependent variable) is the predicted FTP value and X (the independent variable) is the measured emission level from the single mode measurement or the composite emission level from a short test cycle. The regression was developed independently for HC, CO, and NO_x using the data from each of the steady state modes, the two transient mode test cycles, and the Key Mode test.

If the two related emission measurements (X and Y) are plotted graphically, the individual data points will exhibit some degree of scatter about the regression line. The extent to which the data points are scattered is reflected by the standard error of the estimate. This parameter represents the square root of the mean of the squares of the deviations about the regression line:

$$SEE = [\Sigma(\hat{Y} - Y)^2/\bar{n}]^{\frac{1}{2}}$$

The summation is made over all "n" data points. The standard error of the estimate provides a measure of the variation in the data and is used as the basis for establishing confidence limits within which a given percentage of the predicted values can be expected to fall.

Associated with each of the simple regressions is a coefficient of correlation which ranges in value from zero to one. This parameter is a measure of the degree of association between the two variables relative to the range of values observed for the Y variable, or FTP measurements. The following equation provides a convenient operational definition of the coefficient of correlation,although it is not usually calculated in this manner:

$$r = [1 - (SEE^2/V_Y)]^{\frac{1}{2}}$$

where V_y is the variance of the FTP data (or the square of the standard deviation) and SEE is the standard error of the estimate of the regression equation. A value of one indicates perfect correlation, and zero indicates the lack of any association between the two variables. The coefficient not only represents the accuracy of the regression, but also the significance of the fit associated with the dispersion or variance of the particular data set observed. For any given deviation about the regression line, the significance of the correlation improves (coefficient of correlation increases) as the variance of the observed data set increases.

The standard error of the estimate does not always provide a measure of comparison for different data sets because the standard error is expressed in the original units of the dependent variable (Y). For example, the standard error of a regression of HC measurements cannot be directly compared to the standard error of a regression of CO emission measurements. Alternatively, the coefficient of correlation is an absolute term expressed as a fraction. Therefore, this parameter eliminates the problems incurred when comparing two associated series of data which have different dispersions and different units.

A multiple regression analysis was performed for the multiple mode emission measurements wherein each mode is entered into the regression equation. The multiple regression equation is of the form:

$$\hat{Y} = a + bX_1 + cX_2 + dX_3 + \ldots\ldots\ldots\ldots$$

where $\hat{Y}$ again represents the predicted FTP value and the X_i represent the independent emission measurements from each individual measurement mode. Parameters analagous to those calculated for the simple regressions were determined for the multiple regressions. Thus,the standard error of the estimate reflects the average deviation between the predicted FTP value and the true FTP value,providing a measure of the accuracy of the prediction, or the confidence interval associated with the prediction. A coefficient of multiple determination (R) is calculated which represents the degree of scatter around the regression relative to the variance of the dependent variable (the measured FTP emissions) observed for the test fleet.

The regression analysis of the six steady state modes included a multiple stepwise regression where the individual measurement modes are added to the regression equation in an iterative or stepwise fashion. If any one mode does not add a statistically significant amount of information to the regression (i.e., substantially reduce the standard error of the estimate), it is dropped from the equation.

2.5.3 RESULTS OF THE CORRELATION ANALYSIS

The results of the correlation analysis are summarized in Table 2-24. For each test procedure or individual test mode evaluated, the standard error of the estimate and the appropriate correlation coefficient (either the simple coefficient of correlation, r, or the multiple coefficient of determination, R) are presented for hydrocarbons, carbon monoxide, and oxides of nitrogen. The results are presented for only one of the four test fleets,although the parameters are summarized for the before service and the after service emission measurements individually. The results for the remaining three test fleets did not differ from those presented here to the extent that the conclusions based upon the data presented here would be contradicted.

In general, the results of the regression analysis indicate that the best correlation is always achieved for the dynamic (loaded) mode tests which provide a measure of the mass emission rate. The correlation coefficients indicate that there is no significant advantage of the transient mode tests over the steady state modes or the Key Mode test for the measurement of either HC or CO. However, the transient mode tests do appear to achieve somewhat better correlation for the NO_x emission measurements.

The same relative trends among the alternative test procedures are observed for the volumetric emission measurements of all three pollutants. Among all of the test measurements, the idle mode volumetric measurement consistently achieves the lowest degree of correlation with the Federal Test Procedure. The difference is most substantial for the measurement of oxides of nitrogen.

TABLE 2-24

CORRELATION COEFFICIENTS FOR SHORT TEST EMISSION MEASUREMENT PROCEDURES

1972 FTP REGRESSION BEFORE SERVICE

CALIFORNIA IDLE INSPECTION FLEET DATA

		Correlation Coefficient			Standard Error of Estimate Grams Per Mile		
Test Procedure	Emission Measurement	HC	CO	NOx	HC	CO	NOx
Federal Short Cycle	Mass	0.94	0.81	0.74	2.5	32	1.1
Seven Mode Cycle	Mass	0.91	0.70	0.70	3.1	38	1.1
Key Mode (multiple regression)	Mass	0.96	0.81	0.66	2.2	32	1.2
Steady State Modes (mult. regression)	Mass	0.96	0.82	0.71	2.2	32	1.2
Idle Mode	Mass	0.80	0.62	0.15	4.4	42	1.6
Seven Mode Cycle	Volumetric	0.57	0.77	0.43	6.0	34	1.4
Key Mode (multiple regression)	Volumetric	0.79	0.68	0.61	4.5	40	1.3
Steady State Modes (mult. regression)	Volumetric	0.81	0.68	0.63	4.4	40	1.3
Idle Mode	Volumetric	0.35	0.50	0.02	6.8	46	1.6

TABLE 2-24
(continued)

CALIFORNIA IDLE INSPECTION FLEET DATA - AFTER SERVICE

Test Procedure	Emission Measurement	Correlation Coefficient			Standard Error of Estimate grams per mile		
		HC	CO	NOx	HC	CO	NOx
Federal Short Cycle	Mass	0.67	0.50	0.68	3.1	40	1.1
Seven Mode Cycle	Mass	0.77	0.62	0.60	2.6	36	1.2
Key Mode (multiple regression)	Mass	0.88	0.74	0.62	2.0	31	1.2
Steady State Modes (mult. regression)	Mass	0.91	0.78	0.73	1.8	29	1.0
Idle Mode	Mass	0.73	0.43	0.23	2.9	41	1.5
Seven Mode Cycle	Volumetric	0.80	0.68	0.42	2.5	33	1.4
Key Mode (multiple regression)	Volumetric	0.85	0.62	0.56	2.2	36	1.3
Steady State Modes (mult. regression)	Volumetric	0.87	0.60	0.62	2.0	37	1.2
Idle Mode	Volumetric	0.64	0.27	0.09	3.2	44	1.5

In general, the correlation coefficients are lower for all test procedures after service. This is not unexpected, however, since the effect of maintenance tends to reduce the variance, or the dispersion, of the fleet emission levels. The standard error for CO and NOx measurements is not significantly changed following service; whereas, the standard error of the HC measurements is reduced for all test procedures except the Federal Short Cycle and the idle mode mass emission measurement.

The results of the multiple stepwise regression are summarized in Table 2-25. The coefficients of multiple determination are shown for each multivariate regression using various combinations of the six steady state modes and the idle mode (0 mph) with volumetric measurements. The individual test modes are entered into the regression equation such that the maximum improvement in the correlation is achieved for each iteration of the regression. The simple coefficients of correlation are also shown for each test mode independently.

The multivariate regressions indicate only a marginal improvement of the information content by adding more than two or three operating modes to the regression equation. The same trends are observed for both HC and CO measurements. With respect to an inspection program, the additional time and cost incurred by including emission measurements in all seven modes would not be justified.

The single modes demonstrating the best correlation with the FTP are consistently observed to be loaded cruise modes; the simple r values being substantially higher than the idle mode (0 mph) r value. With respect to both HC and CO values, the correlation coefficient for the best loaded mode is around 0.7 as opposed to 0.4 to 0.5 for the idle mode. Better correlation is achieved for HC measurements than for CO measurements.

TABLE 2-25

RESULTS OF STEADY STATE MODE STEPWISE MULTIPLE REGRESSION

1972 FEDERAL TEST PROCEDURE VS. VOLUMETRIC STEADY STATE MODES

CALIFORNIA IDLE INSPECTION FLEET - BEFORE SERVICE

Variables Entered in Regression Analysis	CORRELATION Multiple R	COEFFICIENTS Single Mode	Simple r
Hydrocarbons Emissions			
20 mph	.763	20 mph	.763
20, 40 mph	.802	40 mph	.762
20, 40, 10 mph	.805	10 mph	.532
20, 40, 10, 0 mph	.811	0 mph	.350
0, 10, 20, 30, 40, 50, 60 mph	.813		
Carbon Monoxide Emissions			
40 mph	.652	40 mph	.652
40, 10 mph	.673	10 mph	.560
40, 10, 30 mph	.675	30 mph	.403
40, 10, 30, 20 mph	.677	20 mph	.570
0, 10, 20, 30, 40, 50, 60 mph	.678	60 mph	.480

2.5.4 CONSIDERATIONS OF THE NEED FOR CORRELATION

The results observed in the Short Cycle Study indicate that an idle mode emission inspection and a loaded mode emission inspection would be equally effective for an in-use vehicle inspection program. However, the poor correlation between the idle emission measurements and the FTP raises concern regarding the continued effectiveness of an idle inspection program for a number of reasons.

- The sizeable emission reductions observed in the idle inspection fleets appear to be due, in large part, to the prevalance of excessive maintenance. It is expected that competitive and consumer pressure will eventually constrain the maintenance procedures such that only repairs and adjustments necessary to achieve compliance with the idle test will be performed.
- Over time, the mechanics and vehicle owners are likely to learn how to "beat" the idle test by inducing certain adjustments which lower idle concentration measurements and which have no effect, or perhaps increase, true mass (FTP) emissions.
- Further evaluation of alternative inspection approaches must consider the capability of the specific test procedures for testing the advanced control systems which may be used in future model year vehicles. There is little assurance that the idle test will be adequate for evaluating the emission control performance of new motor vehicles (post-1973). As these model year groups comprise an increasing fraction of the vehicle population, the effectiveness of an idle inspection program will be reduced accordingly.

Effectiveness for Current In-Use Vehicles

The low level of maintenance necessary to comply with the idle mode emission test is not expected to achieve the sizeable reductions observed in the Short Cycle Study. The discrepancy between the expected effect and the observed results may be explained by the tendancy of the mechanics participating in the study to perform a substantial amount of excessive repair.

The Short Cycle Study was designed to evaluate the capability of the two inspection procedures in screening vehicles with excessive emissions attributable to engine malfunctions. To approach the actual conditions which would exist immediately following implementation, a sample of private garages was selected from the present service industry to perform the required maintenance on the "failed" vehicles. The mechanics were provided with instruction in emission diagnostic procedures only to the extent that could be expected prior to the implementation of a real State program. A detailed analysis of the repair actions revealed that the mechanics consistently resorted to conventional repair procedures rather than utilizing the diagnostic content of the emission test results provided with each vehicle they received.

Assuming that the test fleets were statistically valid samples of the vehicle population, the fleet emission distribution would be similar to the distribution of elapsed time since the last conventional maintenance or tune-up, i.e. low emissions would correlate with recent maintenance. Therefore, the use of any two screening tests which reflect the elapsed time without maintenance and which are designed to fail a large fraction of the test fleet should identify two equivalent vehicle sub-sets with respect to the distribution of both emissions and malfunctions. This phenomenon appears to have occurred in the Short Cycle Study; both the idle mode test and the cruise mode test failed statistically equivalent sub-sets within each of the independent test fleets. Since the sub-sets of failed vehicles were identical between the two fleets, and the repair agencies utilized identical maintenance techniques, equivalent emission reductions would have to be expected.

Although the mechanics were not informed of the specific purpose of the study, they were coginzant of some type of performance evaluation. Knowing that the program in some way was evaluating the reduction of motor vehicle pollution which could be achieved by proper repair and adjustment of the automobile, the mechanics would naturally try to demonstrate the importance of requring more frequent maintenance. Therefore, their effort to provide any and all maintenance, which in their judgement was necessary, is understandable. This tendancy was further enhanced by the design of the test program which did not require any direct interface between the repair agency and the vehicle owner.

Irrespective of the Short Cycle Study results, it is reasonable to assume that the competitive and consumer pressure that would be present in a real program would tend to eliminate this "shotgun" maintenance approach and eventually support only repair and adjustment of those components necessary to comply with the inspection test standards.

At present, the empirical data base is insufficient to define the level of effectiveness which can be expected as "shotgun" maintenance procedures are gradually eliminated. However, the regression equations derived from the results of the Short Cycle Study provide a means for estimating the resultant mass emission reduction that may be achieved following the implementation of an idle inspection program. The methodology involves utilizing the idle mode regression equations derived from the fleet emission levels before and after service to predict fleet mean emission levels as a function of the observed idle mode emission levels before and after service. The absolute difference between the before-service and after-service predicted emission levels is divided by the measured as-received mass (FTP) emission level to obtain an index of effectiveness. This analytical approach relies upon the following assumptions:

- The change in idle mode emissions observed in the Short Cycle Study will be achieved by an idle inspection program.
- The mechanics will not perform "shotgun" maintenance, but will perform repairs and adjustments necessary to comply with the idle mode emission test.
- The repair actions taken by the mechanics will not be those which "beat" the idle test.

The predicted mass emission reductions and the observed mass emission reductions based on the Short Cycle Study results are summarized in Table 2-26 for each of the four independent test fleets. The average reduction for the four fleets indicates that the relative

TABLE 2-26

COMPARISON OF OBSERVED FLEET EMISSION REDUCTION[1]
and
PREDICTED EMISSION REDUCTION USING IDLE REGRESSION EQUATION

	Hydrocarbons			Carbon Monoxide		
	Before Service		After Service	Before Service		After Service
California Fleet I						
Observed Level	7.46		5.82	89.88		76.31
Predicted Level	6.97		6.47	87.56		80.13
Observed Change		22%			15%	
Predicted Change		6.7%			8.3%	
California Fleet II						
Observed Level	8.18		5.43	94.81		71.78
Predicted Level	7.08		6.10	87.14		75.28
Observed Change		34%			24%	
Predicted Change		12%			12%	
Michigan Fleet I						
Observed Level	8.52		6.69	97.73		78.95
Predicted Level	8.53		6.88	94.88		80.56
Observed Change		21%			19%	
Predicted Change		20%			15%	
Michigan Fleet II						
Observed Level	7.69		6.00	94.8		77.39
Predicted Level	7.09		6.31	89.52		78.60
Observed Change		22%			18%	
Predicted Change		10%			11.5%	

I = idle fleets (150 vehicles each)

II = key mode fleets (150 vehicles each)

Total Relative Effectiveness $HC = \frac{12.2}{25.0} = .49$

$$CO = \frac{12}{19} = .63$$

---

[1] 1972 Federal Test Procedure (CVS-C)

effectiveness of the idle mode inspection approach would be 0.49 for HC and 0.63 for CO; i.e., the magnitude of the HC emission reduction would be approximately one-half that achieved by a loaded mode inspection program.

As stated previously, the above analysis assumes the inspection procedures prevent the possibility of "beating" the idle mode test. Certain idle adjustment parameters are known to effect a reduction of idle concentration levels while concurrently increasing mass emission levels in other operating modes. Accordingly, many adjustments made to achieve compliance with an idle inspection may, in fact, have a negative effect on air quality.

To evaluate the effect on emission levels induced by various engine adjustments and component malfunctions, a controlled study was carried out in support of the APRAC/CAPE-13 Project.[9] Emissions response coefficients were calculated for specific engine parameters. These response coefficients represent the unit emission change per unit parameter change. The parameter change may result from an adjustment or from mechanical deterioration over time. The coefficients are shown in Table 2-27 for idle mode concentration measurements, cruise mode concentration measurements, and FTP mass measurements.

Any parameter change causing an idle emission response which is significantly different (in sign or magnitude) from the mass emission response is capable of being used to "beat" the idle test. Table 2-28 places these effects in perspective for some typical engine adjustments and malfunctions. The total effects and the percent change for each case are relative to the tuned emission level for the 1971 California vehicle.

TABLE 2-27

EMISSION RESPONSE COEFFICIENTS *

--- Hydrocarbon Response ---

Parameter	Idle Mode Concentration (ppm)	50 mph Cruise Mode Concentration (ppm)	FTP Mass (gpm)
% Idle CO	13.43	.60	.10
Idle rpm	-.34	-.02	00
Basic Timing	11.55	4.05	.10
Misfire	137.60	128.00	1.80
NOx Device +	105.80	11.20	.60
PCV Valve	-2.97	-6.85	-.18
Air Cleaner	-.09	.09	00

--- Carbon Monoxide Response ---

Parameter	Idle Mode Concentration (Percent)	50 mph Cruise Mode Mode Concentration (Percent)	FTP Mass (gpm)
% Idle CO	1.03	.01	11.43
Idle rpm	00	00	.08
Basic Timing	00	-.01	-1.35
Misfire			
NOx Device	.03	-.02	-7.30
PCV Valve	-.01	-.14	-9.75
Air Cleaner	00	00	.11

--- Oxides of Nitrogen Response ---

Parameter	Idle Mode Concentration (ppm)	50 mph Cruise Mode Concentration (ppm)	FTP Mass (gpm)
% Idle CO	-38.3	-1.8	-.03
Idle rpm	.39	-.04	00
Basic Timing	.43	91.62	.16
Misfire			
NOx Device	40.00	313.6	.72
PCV Valve	-3.94	53.78	.13
Air Cleaner	-.04	-.70	-.003

--- Tuned Emission Level for 1971 California Vehicles ---

TEST	HC	CO	NOx
1972 CVS	4.36gpm	59.2gpm	5.88gpm
Loaded Cruise	125ppm	0.83%	2520ppm
Idle Mode	190ppm	2.88%	177ppm

* Change in emissions per unit parameter change (Delta E/Delta P)
Representative of 1971 California vehicles.
Data from APRAC-CAPE-13 Project, TRW and Scott Laboratories (Ref. 9).

+ Ignition timing modifications.

TABLE 2-28

EMISSION RESPONSE DUE TO TYPICAL ADJUSTMENTS AND/OR MALFUNCTIONS

Adjustment or Component Change	HYDROCARBONS Idle ppm	HYDROCARBONS Cruise ppm	HYDROCARBONS FTP gpm	CARBON MONOXIDE Idle %	CARBON MONOXIDE Cruise %	CARBON MONOXIDE FTP gpm	NITROGEN OXIDES Idle ppm	NITROGEN OXIDES Cruise ppm	NITROGEN OXIDES FTP gpm
(a) Adjustment									
Increase rpm +100									
Retard Timing -5 deg									
Reduce Idle CO -0.5%ICO									
TOTAL EFFECT	-98.8	-22.3	-.55	-.52	+.05	+9.03	+56	-461	-.78
PERCENT CHANGE	-52%	-18%	-12.6%	-18%	+6%	+15.3%	+32%	-18%	-13.3%
(b) Malfunction & Adjustment									
Partial Misfire	+138	+128	+1.8	--	--	--	--	--	--
Tune-up:									
Increase rpm +200									
Retard Timing -10 deg									
TOTAL EFFECT	-46	+84	+.80	0	+.1	+30	+74	-907	-1.6
PERCENT CHANGE	-24%	+67%	+18%	0	+12%	+51%	+41%	-36%	-27%
(c) Partial Blockage of Air Cleaner (100 deg)									
EFFECT	-9.1	+9	0	+.01	+.29	+11	-4.4	-70	-.3
PERCENT CHANGE	-5%	+7%	0	+.3%	+35%	+19%	-2.5%	-3%	-5%

Case "a" shows the resultant impact on emission levels for a typical combination of parameter adjustments. The most significant effect to be observed here is the discrepancy between the idle mode CO measurement and the FTP CO measurement. Note that the cruise mode measurement of HC and CO is reasonably representative of the FTP measurement.

Case "b" represents a hypothetical situation to demonstrate the ease with which the idle test can be "beaten." A partial misfire is shown to cause excessive idle HC emissions. Rather than repairing the ignition system failure, the idle mode emissions may be reduced by adjustment of idle rpm and basic timing. The true effect, however, as measured by the FTP, would be 15% and 14% increases of HC and CO respectively.

The diagnostic potential of a loaded mode test is exemplified in case "c." The nominal malfunction is the partial blockage of the air cleaner. The idle mode CO emission response is insufficient to warrant failure of the vehicle; thus the malfunction would remain undetected. Alternatively, the loaded mode CO measurement does indicate an induction system malfunction and thereby provides adequate justification for failure.

Utility of Emission Test Procedures for Inspection of Future Motor Vehicles

Until the operational characteristics of emission control systems which will be employed in future model year vehicles are firmly defined, it is not possible to determine with certainty the adequacy of various emission test procedures in identifying malfunctions of those systems; the the relative importance of identifying various types of malfunctions cannot be determined until operating experience with substantial numbers of those vehicles has been gained. However, some general conclusions can be drawn based upon the general characteristics of various test procedures.

Because it is considered most representative of typical light duty vehicle operation in urban areas, the Federal Certification Test Procedure (FTP) is the standard for measuring vehicle emissions. The limited number of vehicle operating conditions included in an idle mode emission test, as compared with the FTP, makes it improbable that this inspection approach will be useful for detecting certain types of malfunctions in future motor vehicles.

The potential shortcomings of the idle mode test for future control systems are exemplified by its inability to diagnose malfunctions of exhaust gas recirculation (EGR) systems which are currently being used by most automobile manufacturers to ensure compliance with the 1973 Federal NOx emission standards. When the EGR valve is functioning properly, there is no recirculation of the exhaust gas during idle operation; therefore, the system provides no reduction of idle NOx emissions. A malfunction of the EGR system causing an increase in NO_x

emissions during loaded operating modes would not result in a concurrent increase in idle mode emissions. The malfunction would, therefore, remain undetected by an idle test measurement.

A loaded emission test, on the other hand, includes a wider range of operating conditions and should be more generally useful in testing future vehicles, although all current short emission tests are hampered by their inability to measure cold-start emissions, which will become increasingly important for vehicles equipped with catalytic and thermal reactor emission control systems.

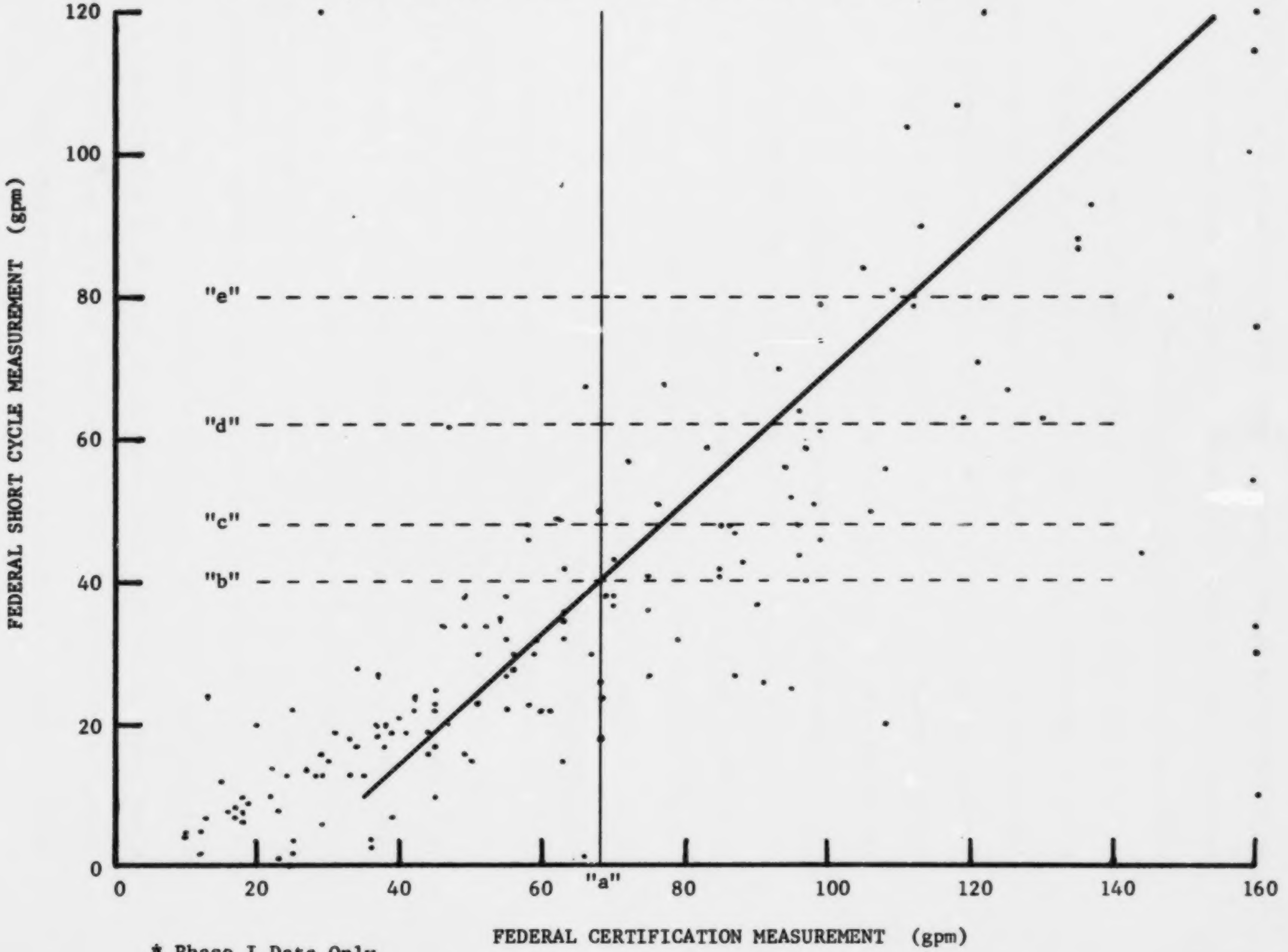
The same type of considerations would also apply to the choice of emission inspection procedures to be used for vehicles retrofitted with exhaust emission control systems, which must receive periodic inspection and maintenance to ensure the effectiveness of the retrofit emission controls (see Chapter 3).

Additional Considerations

The evaluation of alternative inspection procedures must also consider their relationship to enforcing the warranty provisions set forth in Section 207 of the Clean Air Act. That section authorizes the EPA to establish regulations requiring automobile manufacturers to warrant the emission control performance of every new motor vehicle for the vehicle's useful life. To implement this provision, Section 207 requires that there be available short test procedures which achieve adequate correlation with the FTP. While the definition of adequate correlation is yet to be established, it is clear that those short tests which achieve the highest degree of correlation will be most likely to satisfy the requirements for adequate correlation. The correlation analyses have

FIGURE 2-13

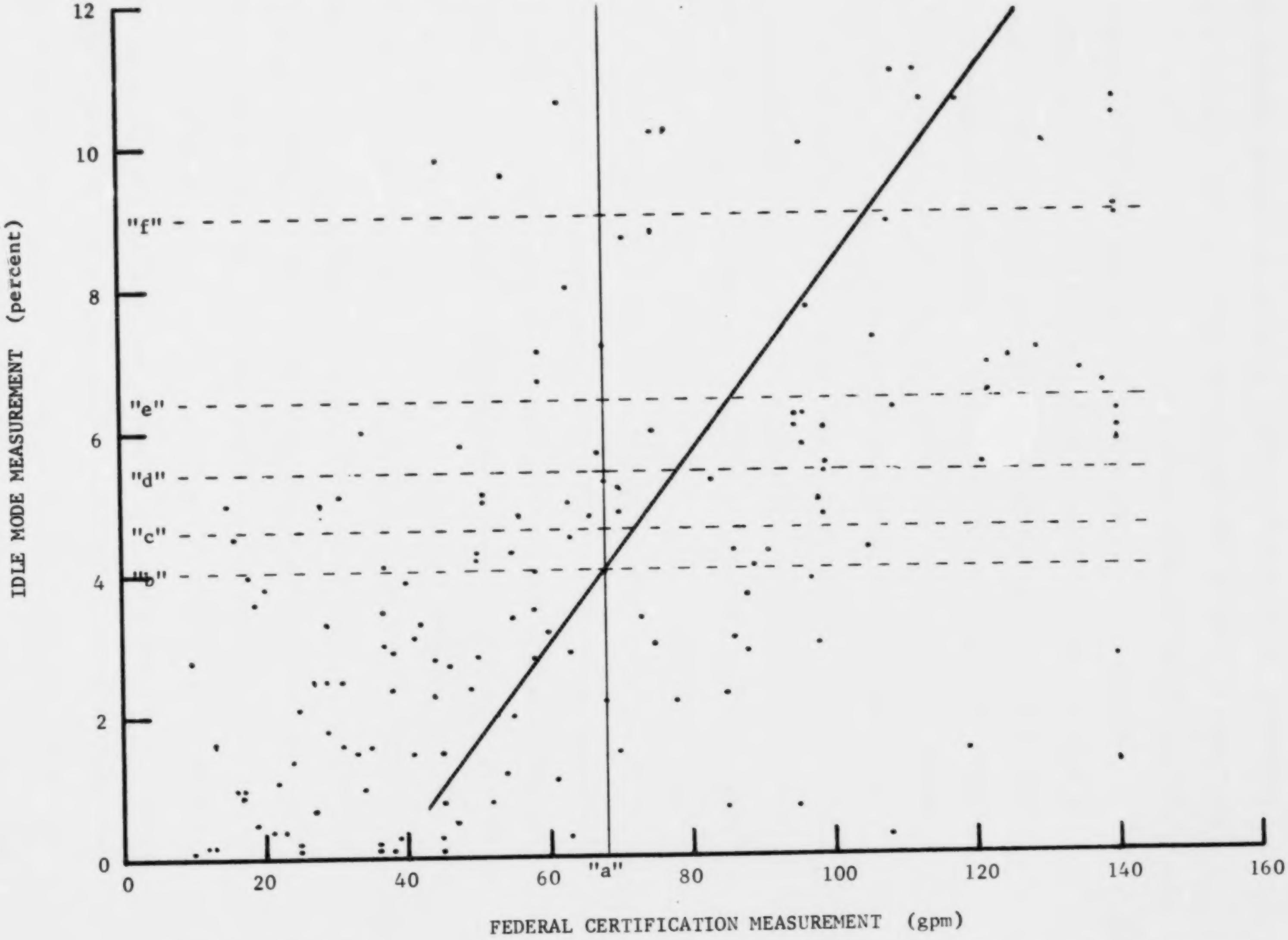
CARBON MONOXIDE EMISSIONS *
FEDERAL SHORT TEST CYCLE VERSUS FEDERAL CERTIFICATION TEST CYCLE



* Phase I Data Only

FIGURE 2-14

CARBON MONOXIDE EMISSIONS *
IDLE MODE TEST CYCLE versus FEDERAL CERTIFICATION TEST CYCLE



* Phase I Data Only

Correlation Coefficient = .375

consistently shown that for current vehicles the dynamic (loaded) tests, as a general category, achieve significantly higher correlation with the FTP than do the idle mode tests.

The States are not required to consider the feasibility of enforcing the warranty provisions in the design of their transportation control plans, and the warranty requirement (Section 207(b)) would not apply to current vehicles in any case. However, any enforcement program which imposes a burden of responsibility upon the private citizen, should also provide adequate protection for the vehicle owner to ensure that the burden of non-compliance is only placed upon those who are truly liable. Accordingly, the enforcement of the warranty provision may directly affect the public acceptability of any enforced in-use vehicle inspection program.

The selection of an individual inspection test requires the development of criteria for determining what degree of correlation is adequate to satisfy the warranty provisions. The following analysis provides a qualitative means of making such a determination.

For illustrative purposes, it is assumed that the points marked "a" in Figures 2-13 and 2-14 represent the Federal emission standard for all the vehicles in the sample fleet. The points marked "b", "c", "d", and "e", represent hypothetical cutpoints for a State inspection program. A higher cutpoint results in a lower rejection rate, and thereby reduces the fleet emission reduction potential of the program. Any vehicle which is above the inspection cutpoint, and is to the left of point "a", is defined as an error of comission. These vehicles are erroneously identified as excessive emitters. Any vehicle which fails the inspection criteria and is to the right of point "a" is a valid failure.

The feasibility of enforcing the warranty will be determined by the frequency of comission errors among the vehicles which fail the short test. The probability of a commission error can be reduced by raising the inspection test failure criteria. At any cutpoint, a commission error is still defined as any failed vehicle to the left of point "a." Therefore, a tradeoff exists between the feasibility of enforcing the warranty and the fleet emission reduction achieved by the inspection strategy. The degree of correlation between the two test procedures is a measure of the extent to which the short test failure criteria must be raised to reduce the errors of commission to an acceptable level.

Table 2-29 presents the results of applying this type of analysis for the Federal Short Test procedure and the Idle Mode test procedure. The rejection rate, the frequency of commission errors, and the fleet emission reductions are shown for selected short test cutpoints.

The results of this analysis are not intended to provide sufficient information to determine the failure criteria which should be used in a State program. The test fleet used to demonstrate this analysis was composed of the total model year mix in the present California vehicle population. The individual failure criteria would have to be determined for each model year such that the commission errors were reduced to an acceptable level. However, Table 2-29 does demonstrate the impact of the tradeoff between commission errors and the fleet emission reduction potential for two levels of correlation.

TABLE 2-29

ERRORS OF COMMISSION FOR TWO REPRESENTATIVE SHORT TEST PROCEDURES

Test Type	Rejection Rate	Frequency of Commission Errors % of Failed Vehicles	Fleet Emission Reduction After Maintenance (CO Emissions)
Federal Short Cycle	50%	32%	17%
(Corr. Coef. = 0.721)	40%	22%	15%
	30%	18%	14%
	20%	10%	8%
	10%	7%	5%
Idle Mode Test	50%	43%	17%
(Corr. Coef. = 0.375)	40%	40%	15%
	30%	30%	10%
	20%	30%	12%
	10%	27%	8%
	5%	14%	4%

It appears that the Federal Short Cycle, which exhibits a correlation coefficient of 0.721, can achieve a significant emission reduction while maintaining only a 10% to 15% chance of failing a low-emitting vehicle. Alternatively, the probability of a commission error is greater than 20% for Idle Mode failure criteria which only achieve a rejection rate of 10%.

Conclusions

The results of the Short Cycle Study comparing the idle emission inspection procedure and a loaded cruise mode emission inspection procedure are somewhat misleading and may indicate erroneous conclusions regarding the relative effectiveness of the two inspection approaches. Although the idle inspection fleets and the cruise mode inspection fleets achieved statistically equivalent emission reductions, the correlation studies support a number of reasons for questioning the effectiveness of the idle inspection approach:

1) The low level of maintenance required to comply with the idle mode emission test will result in substantially smaller reductions than those expected for a loaded mode test.

2) The tendancy to perform engine adjustments which "beat" the idle mode test rather than effecting proper repair of malfunctioning components will degrade the reductions achieved by an idle inspection program.

3) The idle mode emission test is least likely to be of utility for the evaluation of the emission control performance of future motor vehicles.

2.6 CONCLUSIONS

This chapter has discussed, based upon currently available data, the feasibility, emission reduction effectiveness, and cost of inspection/maintenance approaches to reducing emissions from in-use vehicles. The objective of this chapter has been to provide estimates of the effectiveness and cost of such programs which will be useful to the States in the initial evaluation and planning of motor vehicle inspection/maintenance programs. Prior to, and during, the implementation of such programs, additional investigation and evaluation of a number of factors will be necessary to ensure that the extensive resources which may be committed to an inspection/maintenance program will provide an adequate return in terms of emission reductions.

The principle conclusions which can be drawn at this time regarding inspection/maintenance approaches are summarized in the following paragraphs.

Effectiveness

* Significant reductions in the overall emissions of HC and CO from the current light duty vehicle population can be achieved through requiring additional maintenance beyond that which the vehicles now receive voluntarily. Major changes in NO_x emission levels from such vehicles are not anticipated as a result of providing the additional maintenance. At any one time, significant reductions in the emission levels of approximately 50% of the current in-use light duty vehicle population could be achieved through a requirement for additional maintenance.

* The inspection and maintenance of sample fleets has achieved initial emission reductions of up to 25% in exhaust HC and up to 19% in CO averaged over the entire fleet. No statistically significant changes in the average emissions of NOx were found.

* Deterioration of vehicle emission control performance between periodic inspection/maintenance events will cause the average emission reductions achieved by an inspection/maintenance program over time to be less than the initial reductions observed for the test fleets. A preliminary estimate, based upon an analysis of the current frequency and distribution of voluntary maintenance of emission-related components, indicates that inspection/ maintenance on an annual basis may be expected to achieve average reductions over time of up to 12% in light duty vehicle exhaust HC emissions and up to 10% in light duty vehicle CO emissions. Larger reductions could be achieved with more frequent inspection/maintenance.

* Mean initial emission reductions observed for emission inspection approaches are larger than those observed for engine parameter inspection or mandatory maintenance approaches; however, current data do not permit the relative effectiveness of these approaches to be differentiated at a 90% confidence level.

Cost

* Annual emission inspection in State-operated lanes using a short, loaded-mode test procedure is estimated to cost approximately $2 per vehicle, including amortization of capital investment and operating costs. Extensive engine parameter inspection utilized in a licensed private garage system is estimated to cost approximately $8 per vehicle.

* Repair costs observed in fleet studies of inspection/maintenance approaches indicate that an average repair cost of $20 to $30 is typical for vehicles failing an emission or engine parameter inspection, although an extensive mandatory maintenance requirement could cost up to $60 per vehicle.

* The true net cost of maintenance required by an inspection/maintenance program will depend upon the number of vehicles failing the inspection and the extent to which maintenance required by the program is substituted for maintenance which would normally have been performed voluntarily. It has been estimated that, averaged over the entire light duty vehicle population, the additional cost of maintenance required by an annual inspection/maintenance program in which 30% of the vehicles failed inspection would be about $2 per vehicle.

Comparison of Inspection/Maintenance Approaches

* To the extent that their results relate adequately to emission levels produced during normal urban driving, emission inspection approaches are generally applicable to all in-use light duty vehicles since they directly identify those vehicles having high emission levels.

* Among vehicle fleets tested to date, the frequent coincidence of malfunctions or maladjustments causing high idle mode emissions with malfunctions causing high emission levels under load has resulted in idle emission testing being nearly equivalent to loaded mode emission testing in identifying high emitting vehicles for maintenance. However, the generally poor correlation between idle mode emission measurement and emission levels during typical urban driving indicates that, in practice, some vehicles may be brought into compliance with idle emission inspection standards without significantly reducing their true emission contributions. Correlation with emission levels during typical urban driving is substantially better for loaded mode emission tests.

* Engine parameter inspection and mandatory maintenance approaches depend upon the identification of a relationship between various specific mechanical malfunctions or maladjustments and excessive emission levels. This requires that such approaches be designed for specific model year groups of vehicles, giving consideration to their design and based upon data on the frequency and impact on emissions of various types of malfunctions.

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Chapter 3 RETROFIT OF EMISSION CONTROL TO IN-USE VEHICLES

3.1 INTRODUCTION

Continuing advances in motor vehicle emission control technology suggest that retrofitting more effective emission control systems to in-use vehicles may be useful to accelerate reductions in vehicular emissions. This chapter discusses, in the light of recent EPA evaluations of retrofit emission control technology, the feasibility, emission reduction effectiveness, and costs of retrofit approaches to in-use vehicle emission control.

DEFINITION OF RETROFIT

A retrofit approach can be defined as the addition of any device or system and/or any modification or adjustment, beyond that of regular maintenance, which is made to a motor vehicle after its initial manufacture to reduce emissions. Emission control programs based upon periodic maintenance to restore vehicles to original design specifications are not considered retrofit approaches and are discussed in Chapter 2 of this document. Included in this definition of retrofit would be the conversion of in-use vehicles for operation on gaseous fuels such as propane or natural gas. However, since the evaluation of strategies using alternative fuels requires the consideration of a number of factors not involved in other retrofit approaches, gaseous fuel conversion is mentioned only briefly in this chapter and is discussed in more detail in Chapter 4.

FACTORS WHICH AFFECT THE USEFULNESS OF A RETROFIT APPROACH

The major factors which determine the usefulness of a given retrofit approach can be categorized as follows:

- Applicability to vehicle population
- Emission control potential

- Installation requirements
- Reliability and inspection/maintenance requirements
- Cost
- Acceptability of safety and driveability effects

The potential usefulness of a general retrofit approach (e.g., oxidizing catalytic converter) can be estimated by evaluating representative retrofit systems or devices incorporating that approach according to these criteria. However, before a retrofit program is implemented, extensive testing and evaluation of the specific retrofit systems or devices which will be installed must be performed to ensure that the anticipated emission reductions will be obtained, and that use of the devices will result in no unacceptable effects.

In evaluating a retrofit system, a factor of primary importance is the extent to which its use can reduce emissions. First, the applicability of the retrofit system must be determined. This includes determining the different classes of vehicles (classified according to vehicle weight, engine type, and the types of emission control systems which may already be installed on the vehicles) to which the retrofit system is applicable. The extent of the vehicle population within each of those classes to which the retrofit system can be fitted (e.g., is the retrofit applicable only to specific makes or models) must also be determined. It is desirable that a retrofit system be flexibly designed so as to allow application to a large segment of the vehicle population. Then, the ability of the retrofit system to control each of the three regulated automotive pollutants (hydrocarbons, carbon monoxide, and nitrogen oxides) must be determined; it is also important that the retrofit system not result in emissions of any additional harmful pollutants. The control potential of the system must be established for each different class of vehicles to which it may be applied.

Before a specific system is selected for widespread use, the factors influencing its installation must be evaluated. These include availability of an adequate supply of retrofit units, of facilities equipped to install the system, and of manpower capable of competently installing the system.

Factors which may affect the continued effectiveness of the system in use must also be considered. The reliability of the system must be established and the need for periodic inspection and maintenance of the retrofit system determined. In addition, the need for normal maintenance, such as periodic tune-up, of vehicle systems not part of the retrofit shoudl be considered.

To the consumer, the cost is the sum of three separate terms: initial installed cost, recurring maintenance costs, and associated costs, such as fuel consumption penalties. The cost of the retrofit program implementation to the local jurisdiction for administration and for facilities and manpower needed for inspection is an additional cost factor.

The final area of concern is the retrofit system's acceptability. This analysis involves safety considerations and adverse driveability effects. Possible decreased vehicle life resulting from installation of a retrofit system could be a major consideration in determining system acceptability.

USEFULNESS OF RETROFIT PROGRAMS AS IN-USE VEHICLE EMISSION CONTROL STRATEGIES

Beyond the feasibility, effectiveness, and cost of using retrofit approaches to reduce emissions from individual in-use vehicles, the overall cost and emission reductions resulting from implementation of programs for installing those devices must be evaluated. In addition to the effectiveness and cost of the devices, this depends upon the number of vehicles to be retrofitted and the magnitude of their collective emissions relative to other sources. These factors vary substantially between air quality control regions and with time; so a thorough analysis of the usefulness of retrofit strategies must be made on a region-specific basis. Therefore, the principal concern of this chapter is with the technical feasibility of applying various retrofit approaches to in-use vehicles, with the cost of typical devices, and the emission reductions per vehicle which can be obtained. As a qualitative example, however, some calculations of overall cost and effectiveness of retrofit strategies based upon the average nationwide vehicle distribution are presented in Section 3.4 of this chapter.

STATUS OF RETROFIT TECHNOLOGY EVALUATIONS

Potentially, retrofitting of emission controls could be considered for in-use light duty and heavy duty vehicles, both gasoline and diesel-powered. However, except for evaluation of certain techniques for reducing smoke and odor emissions from diesel-powered buses [1], EPA evaluations of retrofit emission control have to date considered only gasoline-powered light duty vehicles. The principal reason for this emphasis has been the predominant contribution of that class of vehicles to vehicular emissions in most major urban areas. As a result, while retrofit approaches may be applicable to certain classes of heavy duty vehicles, empirical data on the emission reductions attainable through such modifications are not available at this time. Information is also lacking on the application of retrofit approaches to light duty diesel-powered vehicles; but the extremely small number and generally low emission levels of such vehicles makes them an unlikely candidate for a cost-effective retrofit strategy.

The Environmental Protection Agency has completed two major studies directed toward evaluating the feasibility and emission reduction potential of various retrofit approaches. The approaches have been evaluated and tested specifically in terms of their applicability to light duty vehicles not originally equipped with emission control systems. However, some of the results may be useful in judging the applicability of those approaches to controlled vehicles as well. One of these studies was designed as an overall survey of potential retrofit approaches and employed no extensive vehicle fleet testing, although limited testing of several retrofit systems was performed. This study provides a comprehensive assessment of the types of technology currently being applied in developing retrofit devices,as well as a limited evaluation of the range of emission reductions that can be obtained by applying the more promising of those approaches to pre-controlled light duty vehicles. The major findings of this study are discussed in Section 3.2.

The second study was a more extensive evaluation of one relatively inexpensive retrofit device. This study involved the evaluation of the retrofit system through testing it on a fleet of over one hundred pre-controlled automobiles. The major results of that study are discussed in Section 3.3.

3.2 SURVEY OF RETROFIT APPROACHES

3.2.1 DESCRIPTION OF PROGRAM

Through a contract, the Environmental Protection Agency has conducted a survey of currently available retrofit emission control approaches for in-use light duty vehicles. The purpose of the survey was to identify which approaches are feasible for retrofit emission control and to provide a preliminary evaluation of their effectiveness and cost in reducing emissions from pre-controlled automobiles. The study considered all potential retrofit approaches except systems employing lean idle mixture adjustment and ignition timing modification developed by major U.S. automobile manufacturers. This approach was excluded from consideration in the study because a representative device of that type was concurrently being evaluated in a more extensive testing program (see Section 3.3).

The study was initiated by performing a thorough search for all sources of information on retrofit methods and developers. Each source was sent a letter describing the purpose of the program and requesting their participation in the program. Each respondent expressing interest in participating, and who was an actual candidate retrofit method developer, was sent a request to provide data on his device. These data were used to screen the devices by type of retrofit method and to rank them based on their feasibility. The most feasible and representative devices available were selected for a test program.

A fleet of twenty vehicles representative of the pre-controlled used car population was used for testing the performance of the retrofit devices. The cars were tested for emissions and driveability both with and without retrofit.

From the devices selected for testing, four were further screened for additional tests which included durability tests.

To evaluate and compare the different retrofit systems, a methodology was developed that provides quantitative figures of merit or indexes for feasibility criteria, performance, and cost-effectiveness.

3.2.2 RETROFIT TYPES IDENTIFIED

Retrofit devices which are designed to control emissions from gasoline-powered motor vehicles can be classified according to the sources of vehicle emissions they control:

Group 1: Exhaust Emission Control Systems

Group 2: Crankcase Blowby Emission Control Systems

Group 3: Fuel Evaporative Emission Control Systems

Group 4: Combinations of these groups

Table 3-1 shows a more detailed classification structure used to categorize retrofit devices studied in this program.

Some principles and descriptions associated with the principal retrofit systems follow.

3.2.2.1 EXHAUST EMISSION CONTROL SYSTEMS

In controlling exhaust emissions, retrofit devices may be designed either to work on the exhaust gases after they leave the combustion chambers and enter into the exhaust system or to decrease

TABLE 3-1 Retrofit Approach Categories

Group 1. Exhaust Emission Control Systems

- 1.1 Exhaust Gas Control Systems:
  - Catalytic Reactor
  - Thermal Reactor
  - Exhaust Gas Afterburner
  - Exhaust Gas Filter

- 1.2 Induction Control Systems:
  - Air Bleed to Intake Manifold
  - Exhaust Gas Recirculation
  - Intake Manifold Modification
  - Carburetor Modification
  - Turbocharger
  - Fuel Injection

- 1.3 Ignition Control Systems:
  - Ignition Timing Modification
  - Ignition Spark Modification

- 1.4 Fuel Variations:
  - Alternative Fuel Conversion
  - Fuel Additives
  - Fuel Conditioners

Group 2. Crankcase Emission Control Systems
- Closed Systems
- Open Systems

Group 3. Evaporative Emission Control Systems
- Crankcase Storage
- Canister Storage

Group 4. Emission Control Combinations

emission formation by modifications to the induction system or the ignition system, or by the use of fuel conversions or fuel additives. Within these broad categories there are a number of different approaches which can be pursued and for which devices were evaluated in the program.

EXHAUST GAS CONTROL SYSTEMS

One approach for reducing HC and CO is to subject the exhaust to an oxidation process. Among retrofit devices, this is done by using either a catalytic reactor, a thermal reactor, or an afterburner.

In the catalytic reactor approach, the exhaust gas is passed through a canister containing a catalyst for oxidizing HC and CO to carbon dioxide (CO_2) and water. The catalyst is not consumed in the oxidation reaction but deterioration may result from use of certain fuels (such as leaded gasoline). The heat required to initiate oxidation comes from the exhaust gas itself. The oxygen needed for oxidation in the catalytic converter is provided by leaning the fuel mixture at the carburetor or by the addition of supplementary air through installation of an air pump.

The thermal reactor works in much the same way. The reactor is located as close as possible to the combustion chambers where the exhaust gas temperature is usually high enough to support oxidation of HC and CO without having to use a catalyst. In the case of a thermal reactor for rich mixture, adequate oxygen availability is provided by means of air pumped directly into the exhaust manifold, near the exhaust valves.

The exhaust gas afterburner oxidizes the HC and CO in a muffler-type container installed in the exhuast system where an ignition source is provided, such as a spark plug. It is designed to operate with rich fuel mixture gases and, therefore, additional air must be supplied also.

In some designs, reactor approaches to oxidizing exhaust gas HC and CO also indirectly reduce NO. Frequently, a rich fuel mixture is set at the carburetor with the result of inhibited NO formation because of the decreased availability of oxygen in the combustion chambers of the engine.

The purpose of gas filters is to eliminate or reduce particulate emissions such as lead or soot from the exhaust stream. Relatively little work has been done on gas filters in general, and particularly for retrofit purposes. Cyclone separators, glass fiber filters, and scrubber devices would be possible approaches.

INDUCTION CONTROL SYSTEMS

Many retrofit devices of this type operate, in general, on the basis of either leaner air-fuel mixture ratio or improved distribution of the mixture. Lean fuel mixtures provide HC and CO reduction due to the increased oxygen availability. Air bleed to intake manifold, carburetor modifications, and intake manifold modifications are representative methods that produce lean mixtures and/or improved mixture distribution.

Recirculating a portion of the exhaust gases back into the induction system is an effective method to control oxides of nitrogen. The recirculated gas reduces the peak temperature of the combustion process which results in less NO formation.

IGNITION CONTROL SYSTEMS

Most ignition control systems use the principle of retarding the ignition spark. This retardation results in lower peak temperatures in the combustion chamber, and higher temperatures in the exhaust gases; and, therefore, less NO is formed in the engine and more HC is oxidized in the exhaust system.

A simple way of retarding the spark is by disconnecting the vacuum advance of the distributor. This can be done automatically during the appropriate driving modes with different degrees of sophistication according to the type of device.

FUEL VARIATIONS

The substitution of normally gaseous fuels for gasoline is another approach to emission control. Substitute fuels normally considered are liquified petroleum gas (LPG), liquified natural gas (LNG), and compressed natural gas (CNG). Use of gaseous fuels allows leaner mixture operation and can result in lower emissions than for gasoline. In addition, the photochemical reactivity of hydrocarbons in the exhaust gas from gaseous fuels can be substantially less than when gasoline is used; however, there is at present no Federal reactivity scale which allows for quantitative adjustment for this factor.

Fuel additives may also have some potential to reduce emissions. Certain additives, for instance, may reduce engine deposits, and therefore, decrease the tendency for CO and HC emissions to increase as mileage is accumulated.

3.2.2.2 CRANKCASE BLOWBY EMISSION CONTROL SYSTEMS

Engine blowby results when the air- fuel mixture in the cylinder escapes past the piston rings during the compression and power strokes. The vapors enter the crankcase and subsequently escape to the atmosphere.

Crankcase control systems provide a means of circulating ventilation air through the crankcase, mixing with the blowby gases, and recirculating the mixture into the intake manifold, usually through a variable orifice control valve. The flow rate through the valve is normally controlled by intake manifold vacuum.

Typically, ventilation air is drawn either directly from the engine compartment (referred to as an open system), or from the engine air cleaner through a tubing into the crankcase (a closed system).

3.2.2.3 EVAPORATIVE EMISSION CONTROL SYSTEMS

These systems control emissions from fuel that is evaporated from the fuel tank and carburetor. Gasoline tanks and carburetors are vented to the atmosphere on pre-1970 vehicles sold new in California and on pre-1971 vehicles sold new nationally. Losses at the carburetor occur almost entirely during the hot soak period after shutting off a hot engine. Residual heat causes the temperature of the fuel bowl to rise to 150-200°F, resulting in substantial boiling and vaporization of the fuel.

Devices in this group to retrofit used vehicles are not currently available. However, the types of systems employed to control evaporative emissions from new cars are described briefly below.

In one type of evaporative emission control system, the crankcase is used as a storage volume for vapors from the fuel tank and carburetor. During the hot soak period after engine shutdown, the declining temperature in the crankcase causes a reduction in crankcase pressure sufficient to induct vapors. During this period, vapors emanating from the carburetor are drawn into the crankcase. Vapor formed in the fuel tank is carried to a condenser and liquid-vapor separator; the condensate returns to the fuel tank, and remaining vapors are drawn into the crankcase. When the engine is started, the crankcase is purged of vapors by the action of the positive crankcase ventilation system.

In the absorption-regeneration system, a canister of activated carbon traps the vapors and holds them until such time as they can be drawn back into the induction system for burning in the combustion chamber. During a hot soak period, vapor from the fuel tank is routed to a condenser and separator, and liquid fuel is returned to the tank. The remaining vapor, along with fuel vapor from the carburetor, is vented through the canister filled with activated carbon which traps the fuel vapor. When the engine is started, fresh air is purged through the canister and removes the trapped fuel vapor from the activated carbon and carries it to the combustion chamber.

3.2.2.4 EMISSION CONTROL COMBINATIONS

In many cases retrofit systems combine two or more of the retrofit generic types summarized above. Thus, for instance, methods such as "Exhaust Gas Recirculation with Distributor Vacuum Disconnect," "Catalytic Convertor with Distributor Vacuum Disconnect," are basically just combinations of ignition timing modification with exhaust gas recirculation and catalytic convertor, respectively.

3.2.3 RETROFIT EVALUATION METHODOLOGY

To evaluate and compare the performance of the various retrofit systems relative to each other, a methodology was developed that provides quantitative figures of merit or indexes for feasibility criteria, performance, and cost-effectiveness. This methodology is described briefly below; a more detailed description may be found in the contract report [2].

CRITERIA INDEX

The Criteria Index can be expressed by a product of terms each of which can be given the value of either one or zero. It provides an indication as to whether a device will meet the various constraints or limiting values specified for each performance parameter. If the Criteria Index is zero it means the device did not pass one or more of the specified requirements. In that case, the device is sub-standard for at least one of the set of Criteria used. If the Criteria Index is one, it means the device has met all criteria factors.

The Criteria Index includes the following factors:

a. Emission levels for HC, CO, NOx.
b. Safety
c. Critical driveability
d. General driveability
e. Installation cost
f. Recurrent cost
g. Reliability
h. Maintainability
i. Availability

Stated simply, the "Criteria Index" is just a check list to verify if a retrofit passes specified performance requirements.

PERFORMANCE INDEX

The Performance Index provides a more quantitative evaluation of a device, in contrast to the Criteria Index which screens devices for a "yes" or "no" answer as to their basic feasibility. The Performance

Index is a measure of the emission reduction benefit of a device relative to its cost and driveability penalties, and it is expressed by the following equation:

$$\text{Performance Index} = \frac{C_1 \begin{pmatrix}\text{Emission}\\ \text{Index}\end{pmatrix} - C_2 \begin{pmatrix}\text{Driveability}\\ \text{Index}\end{pmatrix} - C_3 \begin{pmatrix}\text{Cost}\\ \text{Index}\end{pmatrix}}{C_1 + C_2 + C_3}$$

This equation weights, according to the weighting coefficeints (C_1, C_2, C_3), the three terms related to emissions, driveability, and cost. These three terms are expressed by corresponding indexes which include scaling factors to bring their values within the same order of magnitude.

The Emission Index is a weighted sum of the reductions of each of the considered pollutants. In applying the methodology, pollutant weighting factors must be chosen based on specific air quality problems to be solved. The Driveability Index is based upon a driveability score determined by assessing what might be considered demerits for a variety of abnormal driving characteristics (rough idle, detonation, surge, etc,). The Cost Index combines those cost parameters which determine the initial cost of the device and the recurrent costs.

To compute the Performance Index, careful judgment must be exercised in assigning the three weighting coefficients (C_1, C_2, C_3) because the weights given to emission reduction, driveability, and cost can greatly influence the value for the Performance Index and the relative ranking of the devices that might be compared. These weighting coefficients can very well be different depending on the requirements or judgment of the specific air pollution control agency using this evaluation methodology.

COST EFFECTIVENESS INDEX

The Cost-Effectiveness Index provides an additional information item to complement the Performance Index. Cost-Effectiveness is usually defined as the ratio of the desired results or the desired output versus the required cost input. In this case the CEI is defined as the ratio of the Emission Index to the Cost Index:

$$\text{Cost-Effectiveness Index} = \frac{\text{Emission Index (per unit reduction)}}{\text{Cost Index (\$/100 miles)}}$$

3.2.4 RESULTS OF PRELIMINARY SCREENING

The data obtained from all sources were analyzed to select the retrofit methods tested in the program. Following the different generic retrofit groups, this section lists, briefly, which retrofit methods were selected for testing and which were evaluated without testing, indicating the fundamental reasons for this distinction. Also, in this section are presented general comments on some of the retrofit methods not tested in the program. Additional details may be found in the contract report[2], where some sixty retrofit devices are evaluated. The results for the retrofit systems tested in the program are presented in Section 3.2.6.

3.2.4.1 EXHAUST EMISSION CONTROL SYSTEMS

EXHAUST GAS CONTROL SYSTEMS

Catalytic Reactor: A retrofit of this kind, with distributor vacuum disconnect was selected for testing. Results are given in Section 3.2.6.

Thermal Reactor: There were no developers of thermal reactors interested in retrofit application. Thus, no thermal reactor was tested, but the contractor evaluated a representative type, finding that it would cost approximately $375.

Exhaust Gas Afterburner: Some devices of this sort were evaluated, but none tested. Study shows that this type device is less reliable than other types of retrofits.

Exhaust Gas Filter: None was selected for testing. Currently there are no regulations for particulate emissions from automobiles. The devices offered to the program were evaluated.

INDUCTION CONTROL SYSTEMS

Two different Air Bleed to Intake Manifold, three distinct Exhaust Gas Recirculation, and three different Carburetor Modification systems were selected for testing, and their results are presented in Section 3.2.6. Other less representative induction control retrofits were also evaluated but not tested in the program.

IGNITION CONTROL SYSTEMS

Two different Ignition Control approaches were selected for testing. Their results are presented in Section 3.2.6. Other less representative systems were evaluated but not tested.

FUEL VARIATIONS

Alternative Fuel Conversion: Typically, substantial emission reductions can be obtained but, in general, the very high cost of the system, and the limited availability of fuels would limit the application only for special fleets or circumstances. Devices offered to the program were evaluated. The feasibility of gaseous fuel conversion as a vehicle emission control strategy is discussed further in Chapter 4.

Fuel Additives or Conditioners: The time constraints of the test program did not permit the mileage accumulation needed to evaluate fuel additives and, therefore, none were tested. However, some data offered to the project on these methods were evaluated.

3.2.4.2 CRANKCASE EMISSION CONTROL SYSTEMS

Considering that there is already substantial information on this emission control system, none was tested. It is expected that reliable devices can eliminate crankcase emissions from uncontrolled cars. However, only some twenty-three percent of the current total car population do not have control for crankcase emissions. Devices offered to the program were evaluated. The conventional crankcase retrofit costs up to $40 installed.

3.2.4.3 EVAPORATIVE EMISSION CONTROL SYSTEMS

No device was tested for evaporative emission control. In this category there were no found devices to retrofit used vehicles. It has been estimated that reliable devices could largely eliminate evaporative emissions from uncontrolled cars; about eighty-five percent of the current total car population do not have evaporative control. The contractor made some evaluation on the basis of the systems supplied in new vehicles. An estimate of $140 was made for the cost to retrofit a used car with evaporative control should such retrofits be made available.

3.2.5 TEST PROGRAM

A summary of the test vehicle fleet, and of the various tests conducted for the retrofit program fleet follows.

TEST VEHICLE FLEET

A total fleet of twenty pre-controlled used cars was used for testing the performance of the retrofits. This fleet was constituted of two replicate subfleets which were bought and operated in Anaheim, California and Taylor, Michigan respectively. The rationale for the replicate fleets was to evaluate differences in retrofit performance between the two fleets which could possibly be attributable to driving conditions, geographical location, and vehicle climatological exposure history at two disparate locations in the United States, or to bias in testing facilities and personnel.

The criteria for selecting the test vehicles were based mainly on the number of vehicles on the road by make and model year prior to 1968, and on the popularity of engine size and type of transmission within that vehicle population. The contract report[2] provides details of the test fleet composition.

Appropriate inspection was applied to ensure that all the cars bought for the test fleet were in a condition representative of normally-maintained vehicles for their corresponding model year.

EMISSION TESTS

As each vehicle was procured, an "as received" exhaust emission test and a driveability test were conducted. The vehicle was then tuned to the manufacturer's specifications to minimize the possibility of engine malfunction during the subsequent retrofit system tests and to provide a reproducible baseline. The vehicle then received a series of baseline exhaust emission tests and driveability tests. After each baseline test, the vehicle was equipped with a candidate retrofit system for exhaust emission and driveability tests. The tests alternated between the baseline and retrofit system tests until testing of all candidate systems was completed.

The 1972 Federal Test Procedure [3] was used to measure the exhaust emissions during the baseline and retrofit tests. The Federal exhaust emission test consists of prescribed sequences of fueling, parking (cold soak), dynamometer operation, sampling, and analytical calculations.

The exhaust test is designed to determine hydrocarbons, carbon monoxide, and oxides of nitrogen on an actual mass emission basis while the vehicle is simulating an average urban trip of 7.5 miles.

Fuel consumption was measured during the baseline and retrofit exhaust emission tests. For this purpose the fuel consumed during the driving cycle was measured by weight. This measurement is representative of fuel consumption in urban driving; however, the statistical significance of these test results is not known.

DRIVEABILITY TESTS

The Automobile Manufacturer's Association (AMA) standard driveability test procedure was used to evaluate the operating characteristics of the vehicles on the road. Basically, the procedure consists of a cold start driveaway following an overnight soak period; and then a hot start driveaway following the cold start portion of the test. The cold start evaluations consist of engine startup, idle , and part throttle and full throttle acceleration modes up to 30 mph. The hot start evaluations consist of a series of cruises, accelerations, idle modes of operation, and hot start restarts. The quality of each driving mode was noted by the driver and recorded by an observer during each mode of operation. Vehicle performance was determined at wide open throttle from 0 to 60 mph by measuring the elapsed time. As explained the Section 3.2.6, four devices were tested more extensively, and in this case some driveability tests were also performed to determine whether environmental extremes (such as high altitude) had any significant performance effect on vehicle driveability when a retrofit device was installed.

DURABILITY TESTS

For the four devices that were tested more extensively (see Section

3.2.6), durability tests were also performed. These tests consisted of driving retrofit equipped cars for 25,000 miles and measuring the exhaust emission by the 1972 Federal Test Procedure at 5,000 mile increments. Mileage accumulation was performed on a test route which consisted of freeway, urban, and city driving, at an average speed of approximately 35 mph. Fuel consumption, and any significant occurences during the mileage accumulation were recorded daily. Durability tests were made with only one car for each device, except in the case of the catalytic converter retrofit which had durability tests on two vehicles. This device requires the use of unleaded fuel, and in one of the two cars only this fuel was used; in the other car a tank refill with leaded premium gasoline was made every 2500 miles to determine the influence of occasional exposure to leaded fuel on the performance of the catalytic converter.

3.2.6 RESULTS FOR RETROFIT SYSTEMS TESTED IN THE PROGRAM

3.2.6.1 GENERAL RESULTS

As identified in Section 3.2.4, eleven retrofit devices were selected for testing in this program. Table 3-2 lists these devices. From these, four devices were selected for more extensive testing. These four devices were selected to cover representative retrofit types, considering their performance potential, and also the availability of retrofits to test in all of the fleet cars.

All eleven devices were submitted to exactly the same test procedures for emissions and driveability, the only difference being that the four devices tested more extensively received up to eighteen complete

TABLE 3-2 RETROFIT SYSTEMS TESTED

Devices Receiving more than 3 Tests (up to 18)	Contract Report[2] Identification Number
* Air Bleed to Intake Manifold (controlled by a poppet valve)	1
* Catalytic Converter with Distributor Vacuum Advance Disconnect	96
* Ignition Timing modification with Lean Idle Adjustment	175
* Speed-Controlled Exhaust Gas Recirculation with Distributor Vacuum Advance Disconnect	246
Devices Receiving up to 3 Tests	
* Throttle-Controlled Exhaust Gas Recirculation with Distributor Vacuum Advance Disconnect	10
* Carburetor Modification of Main Nozzle Differential Pressure	33
* Air Bleed to Intake Manifold (controlled by compressible plastic balls valve)	42
* Electronic-Controlled Distributor Vacuum Advance Disconnect and Careburetor Lean Idle Modification	69
* Variable Camshaft Timing	245
* Carburetor Main Discharge Nozzle Modification	288
* Variable Venturi Carburetor	295

tests, while the other seven devices received up to three complete tests.

Descriptions of the four device and their more important results. are presented separately in the following subsections. Table 3-3 lists the main results for all of the eleven devices tested in the program.

3.2.6.2 AIR BLEED TO INTAKE MANIFOLD (Contract Report Identification No. 1)

DESCRIPTION

This type of device is an air valve that enables the air-fuel ratio to be increased by metering additional air to the intake manifold in accordance with intake manifold vacuum.

The specific device tested consists of a cylinder incorporating an oil-damped air valve, an air intake adapter plate, and an air bleed hose. The air valve cylinder mounts in the engine compartment and the adapter plate installs between the existing carburetor and the intake manifold. The hose connects the air valve to the intake adapter plate.

EVALUATION RESULTS

Emission Reductions

Pollutant	Percent Reduction Pooled Mean	90% Confidence Intervals for Mean % Reduction	Statistical Significance
HC	21	10 to 32	Significant Reduction
CO	58	22 to 80	Significant Reduction
NO_x	-5	-15 to 5	Insignificant Increase

Installed Cost: $56 to 64

Fuel consumption, as measured during 1972 Federal Emission Test Procedure: 4% improvement, i.e., more miles per gallon. Statistical significance of change not known.

TABLE 3-3

RETROFIT DEVICE TEST RESULTS*

Device	Ident. No.	No. of Tests	Mean % Reductions from Tuned Baseline HC	CO	NOx	Installed Cost($)**	Driveability	Reliability (MMBTF)+	Maintenance Interval and Requirements	Installation Time (Hrs.)++
Air bleed to intake manifold	1	18	21	58	(a)	56 to 64	Acceptable(b)	75,000	12,000 mi. 0.3hr./$7.00	1.25
Catalytic converter with distributor vacuum advance disconnect	96	17	68	63	48	143(6 cyl) 175(V-8)	Acceptable(b)	50,000(c)	(d)	4
Ignition timing modification with lean idle adjustment	175	10	19	46	37	45	Acceptable(b)	75,000	(e)	1
Speed-controlled exhaust gas recirculation with distributor vacuum advance disconnect	246	15	12	31	48	89	Acceptable(b)	75,000	6,000 mi. 0.5hr./$7.50	2.25
Throttle-controlled exhaust gas recirculation with distributor vacuum advance disconnect	10	2	37	29	54	71	Acceptable(b)	50,000	12,000 mi. 0.5hr./$7.50	1.25
Carburetor modification of main nozzle differential pressure	33	2	33	46	-43	21	Acceptable(b)	75,000	None requested	1
Air bleed to intake manifold (compressible balls valve)	42	2	23	46	3	23	Acceptable(b)	75,000	12,000 mi. 0.2hr./$2.50	1
Electronic-controlled distributor vacuum advance disconnect and carburetor lean idle modification	69	3	32	29	24	63	Acceptable(b)	75,000	12,000 mi. 0.3hr./$4.00	1
Variable camshaft timing	245	1	-36	-27	21	78	Acceptable(b)	75,000	25,000 mi. 0.5hr./$6.25	2.25
Carburetor main discharge nozzle modification	288	2	4	37	-19	41	(f)	75,000	None requested	1.25
Variable venturi carburetor	295	1	-37	20	25	79	(g)	75,000	12,000 mi. 0.5hr./$6.25	0.75

* Reliability of the data depends upon the number of tests. Emission results for devices with three or fewer tests may not be statistically significant.
** Does not include engine tune-up cost.
+ MMBTF-Estimated mean mileage before total failure.
++ Engine should be in good operating condition. Installation requires automotive mechanic and a shop combustion analyzer.
(a) Not statistically significant.
(b) Tests showed some minor deterioration.
(c) Catalyst life estimated at 25,000 miles. Catalyst requires unleaded fuel without phosphorous additives.
(d) Catalyst replacement cost estimated at $20 for V-8 engines and $15 for 6 cylinder engines. Air pump filter to be cleaned every 12,000 miles at a cost of about $3.
(e) None is requested by the developer. Repair is not possible; in the event of device failure, removal and replacement with a new unit is necessary.
(f) Test showed some improvement (one test).
(g) Test showed poor driveability; however, there is doubt about the validity of this one driveability test

Safety: There are no apparent safety hazards.

Driveability: Some minor deterioration. Acceptable.

Reliability: Estimated about 75,000 miles before total failure.

Installation: Engine should be in good operating condition. Installation takes about 1.25 hours; requires automotive mechanic and shop combustion analyzer.

Maintenance: About 0.3 hours every 12,000 miles, with cost of approximately $7.00.

Applicability to vehicle population: Applicable to most uncontrolled cars having conventional carburetion. In the case of vehicles that already incorporate lean carburetion, installation of air bleed retrofits might cause misfire or adverse driveability characteristics, and therefore, criteria would have to be established to identify leanness limits for cars on which the retrofit could be applied.

Durability results: At the beginning and end of the durability tests, the percentage emission reductions caused by the device were the following:

	Zero Miles (1 test without device, 1 test with device)	25,000 Miles (3 tests with device, 3 tests without device)	25,000 Miles (Device reinstalled and adjusted, 1 test. 3 tests without device)
HC	1%	7%	-7% (increase)
CO	-2% (increase)	7%	64%
NO_x	-16% (increase)	21%	9%

At the 20,000 mile tests, it was discovered that blowby deposits were plugging the PCV (positive crankcase ventilation) tube at its connection with the carburetor. Cleaning of this connection at that mileage reduced

CO from 99 to 45 grams per mile. This problem was not caused by the retrofit device, and it indicates the importance of proper vehicle maintenance and periodic emission inspection to secure the benefits of the emission controls. (The emission tests at zero durability miles indicated unexpected results, however the durability mileage accumulation was undertaken without determining the reasons for these irregularities.)

At 25,000 miles the device was reducing emissions. However, although this is basically a device for reducing CO, it was reducing this emission by only about 7%. On the basis of this poor reduction, the device was reinstalled and adjusted. This brought the CO reduction up to about 64% as indicated in the last column above.

The variability of results at 25,000 miles indicate the sensitivity of the device to proper adjustment. This emphasizes the need for proper installation procedures including the use of a combustion analyzer for proper adjustment.

3.2.6.3 CATALYTIC CONVERTER WITH DISTRIBUTOR VACUUM ADVANCE DISCONNECT
(Contract Report Identification No.96)

DESCRIPTION

This device consists of a catalytic converter installed in the engine exhaust system between the exhaust manifold and the muffler. The converter is located as close as possible to the exhaust manifold. Six cylinder engines use one converter and V-8 engines two converters, one for each exhaust manifold. The converter chamber contains a platinum pellet-type catalyst bed. The bed is filled through a removable plug in the side of the chamber.

For vehicles older than 1968 model year, an air pump is required, in general, to supply the air needed to support the oxidation process in the converter. The pump is mounted on the front of the engine where it can be belt-driven from the drive shaft pulley. On later model cars, the carburetor can generally be tuned to a sufficiently high air-fuel ratio to provide the amount of air needed.

To protect the converter from overheating, a melt-out plug is incorporated in the chamber. If the temperature rises above the level at which the catalyst can operate without being damaged, the plug melts and the exhaust gas is vented directly into the ambient air. In this case the noise will indicate the failure and the necessity for repair. In addition, a thermocouple installed in the converter is wired to an electronic control which energizes a solenoid to divert the air pump output away from the converter if the limit temperature is exceeded.

To disconnect the standard distributor vacuum advance system, a thermoswitch, installed in the radiator water return line is used. The vacuum advance hose is connected through the thermoswitch, which is normally closed, preventing the intake vacuum from actuating the distributor vacuum advance mechanism.

EVALUATION RESULTS

Emission Reductions

Pollutant	Percent Reduction Pooled Mean	90% Confidence Intervals for Mean % Reduction	Statistical Significance
HC	68	53 to 91	Significant Reduction
CO	63	37 to 97	Significant Reduction
NO_x	48	17 to 64	Significant Reduction

Installed Cost: $143 for 6 cylinder engines or $175 for V-8 engines; includes $85 for air pump.

Fuel consumption as measured during 1972 Federal Emission Test Procedure: 1% penalty. Statistical significance of change not known.

Safety: There are no appraent safety hazards (on the assumption that the converter preventive overheat system would be reliable).

Driveability: Some minor deterioration. Acceptable.

Reliability: Estimated about 50,000 miles before total failure. This does not extend to the catalyst which should be changed every 25,000 miles.

Installation: Engine should be in good operating condition. Installation takes about 4 hours; requires automotive mechanic, shop combustion analyzer.

Maintenance: Catalyst should be replaced every 25,000 miles. Cost (including labor), and replacement time are estimated to be as follows:

$15, 0.25 hours, for 6 cylinder engines

$20, 0.30 hours, for V-8 engines

In addition, the pump air filter should be cleaned every 12,000 miles; labor cost will be about $3.

The catalyst requires the use of gasoline without lead or phosphouous additives. However (see durability results below), it appears that occasional use of leaded fuel impairs the efficiency of the catalyst relatively little. Abnormal oil blowby due to worn piston rings can affect the catalyst adversely because of certain oil additives.

Applicability to vehicle population: Applicable to most domestic models. Results presented here are for cars without exhaust controls, however substantial emission reductions should be obtained on controlled vehicles also. The retrofit was not available for VW cars, the only foreign vehicle in the test fleet.

Durability Results: At the beginning and end of the durability tests, the percentage reductions caused by the device were as follows:

Case of unleaded fuel, but one tahkful of leaded premium gasoline every 2,500 miles

	Zero Miles (1 test without device 1 test with device)	25,000 Miles (3 tests with device 3 tests without device)
HC	81%	80%
CO	94%	80%
NO_x	47%	30%

The air bypass valve for overtemperature converter protection was found to be failure prone with mileage accumulation; it had to be replaced twice during the 25,000 mile durability evaluation.

Case of unleaded fuel only

	Zero Miles (1 test without device 1 test with device)	20,000 Miles (2 tests with device 1 test without device)
HC	79%	67%
CO	97%	56%
NO_x	35%	49%

Shortly after the 20,000 mile testing, the catalytic converters were removed from the vehicle and inspected. 87% of the catalyst was recovered from the left converter; however, no catalyst was recovered from the right converter due to high temperature failure of the catalyst retaining screen. The car had been deteriorating rapidly, as indicated by a large increase in engine oil consumption, and the excess burning of oil might have accelerated the activity of the catalyst causing a premature failure of the converter.

The durability tests were terminated after discovery of the loss of catalyst from the right converter. This occurance points out the necessity of periodic emission control system inspection to ensure continued satisfactory operation of this type of retrofit system.

3.2.6.4 IGNITION TIMING MODIFICATION WITH LEAN IDLE ADJUSTMENT

(Contract Report Identification No. 175)

DESCRIPTION

This device consists of an ignition control assembly which is attached to the fender wall under the vehicle hood. It includes the following electronic circuits and components to retard, in a controlled manner, the ignition timing of the engine:

1. A solenoid operated valve which connects or disconnects the distributor vacuum advance.
2. An ignition circuit which regulates the distributor point signal to a retarded condition at vehicle speeds below 35 mph.
3. A sequencing circuit and switch which senses vehicle speed and controls the regulation provided by the first two items.

The device makes three wire connections with the vehicle ignition system, and two hose connections to attach to the carburetor distributor vacuum port and distributor vacuum advance chamber.

The lean idle mixture is obtained by adjusting the carburetor idle mixture setting.

EVALUATION RESULTS

Emission Reductions

Pollutant	Percent Reduction Pooled Mean	90% Confidence Intervals for Mean % Reduction	Statistical Significance
HC	19	9 to 29	Significant Reduction
CO	46	-8 to 77*	*
NO_x	37	27 to 47	Significant Reduction

* There was a large difference between the results for CO found in the two cities. In both cases the mean results indicated CO reduction, but while in Taylor the 90% confidence intervals for the mean percent reduction were 67 to 77% in Anaheim the limits were -8 to 23%, showing a reduction with no statistical significance. The CO data were reviewed for anomalies to determine possible causes of the conflict in results between the two cities, but none were found. However, the operating principle of this device would not allow one to expect large reductions of CO; and, therefore, the mean reduction with lower confidence intervals may be more representative for this device.

Installed Cost: $45

Fuel consumption, as measured during 1972 Federal Emission Test Procedure: 10% penalty. Statistical significance of change not known.

Safety: There are no apparent safety hazards.

Driveability: Some minor deterioration. Acceptable.

Reliability: Estimated about 75,000 miles before failure.

Installation: Engine should be in good operating condition. Installation takes about 1 hour; requires automotive mechanic, shop combustion analyzer.

Maintenance: None is required. Repair is not possible; in the event of device failure, removal and replacement with new unit is required.

Applicability to vehicle population: This retrofit device can be applied to all domestic cars having engines over 140 cubic inches displacement and not equipped with exhaust emission controls, from 1955 to 1967 model years (up to 1965 model year in California).

Durability Results: The device caused the following percentage emission reductions at the beginning and end of the durability test:

	Zero Miles (1 test without device 1 test with device)	25,000 Miles (3 tests with device 3 tests without device)
HC	28%	8%
CO	18%	-24%(increase)
NOx	48%	39%

High CO levels (up to 100% increase from baseline) were measured at the 10,000, 15,000 and 20,000 mile points. These were probably caused by faulty choke operation. The car operated normally but it was found that the choke was partially closed most of the time, and, therefore, the choke was repaired at 23,100 miles.

After 23,500 miles the vehicle alternator diodes failed. The alternator was repaired and mileage accumulation was continued. Coincidentally, the vehicle developed moderate hesitation at heavy engine loads which was particularly noticeable when accelerating on the freeway. Following the 25,000 mile emission test, a diagnosis was conducted to determine the cause for the hesitation under heavy load. The retrofit device was inspected by the developer, and it was revealed that two diodes were malfunctioning in the electronic circuit of the device. It could be that the CO increase recorded at 25,000 miles was due to device malfunction originated by the alternator failure; and if this was the case, the device should include some protection to prevent such malfunctions in the event of vehicle electrical failures.

This shows the necessity of proper vehicle maintenance and periodic emission control system inspection to ensure continued satisfactory emission reductions using this device.

3.2.6.5 SPEED-CONTROLLED EXHAUST GAS RECIRCULATION WITH DISTRIBUTOR VACUUM ADVANCE DISCONNECT (Contract Report Identification No. 246)

DESCRIPTION

In the device tested, the exhaust gas recirculation (EGR) was taken from an exhaust adapter in the exhaust pipe, passed through an EGR valve, and introduced between the carburetor and the intake manifold by means of an intake adapter. A more recent modification by the developer introduces the recirculation exhaust gas through the positive crankcase ventilation (PCV) system.

A speed control allows about 15% of the exhaust gas to be recirculated to the intake manifold whenever the vehicle speed exceeds 26 mph, and it shuts off the recirculation whenever the speed drops below approximately 12 mph. A deceleration switch is also provided to stop recirculation whenever the accelerator pedal is released.

The distributor vacuum advance unit is operated by a solenoid valve which is interconnected in the vacuum advance tube between the distributor and the intake manifold, and to the EGR valve. The vacuum advance operates during exhaust gas recirculation at speeds above 26 mph, and the vacuum advance is disconnected when exhaust gas recirculation is terminated by the speed or accelerator pedal controls.

The speed switch and cable are connected to the speedometer tap on the transmission, and to the EGR valve. The solenoid valve is connected to the speed switch electrically.

EVALUATION RESULTS

Emission Reductions

Pollutant	Percent Reduction Pooled Mean	90% Confidence Intervals for Mean % Reduction	Statistical Significance
HC	12	3 to 21	Significant Reduction
CO	31	6 to 60	Significant Reduction
NOx	48	43 to 52	Significant Reduction

Installed Cost: $35 (At the time of the study the anticipated installed cost was $89; however, since that time the manufacturer has announced that the device will be made available at a price consistent with an installed cost of $35).

Fuel consumption, as measured during 1972 Federal Emission Test Procedure: 7% improvement, i.e., more miles per gallon. Statistical significance of change not known.

Safety: There are no apparent safety hazards.

Driveability: Some minor deterioration. Acceptable

Reliability: Estimated about 75,000 miles before total failure.

Installation: Engine should be in good operating condition. Installation takes about 2.25 hours; requires automotive mechanic, shop combustion analyzer.

Maintenance: Cleaning of exhaust gas recirculation valve and solenoid vacuum valve filter recommended every 6 months/6,000 miles. This would cost about $7.50.

Applicability to vehicle population: The device would be applicable to most domestic cars, from the 1955 model year. Results presented here are for cars without exhaust emission controls. These results include testing on a VW car since the retrofit was available for this foreign vehicle.

Durability Results: The device caused the following percentage emission reductions at the beginning and end of the durability tests:

	Zero Miles (1 test without device 1 test with device)	25,000 Miles (3 tests with device 3 tests without device)
HC	46	-3 (increase)
CO	-8 (increase)	-55 (increase)
NOx	45	10

The car had choke operating problems which were not caused by the retrofit . During the mileage accumulation it was necessary to repair the choke six times. This may explain the bad results for CO emissions.

Also, the speed control switch for the exhaust gas recirculation unit of the retrofit had to be replaced twice during the mileage accumulation ; first because it was damaged, along with the speedometer cable, at a car wash facility; but later this replacement became inoperative and the speed switch had to be replaced again. Inadequate control switch operation could explain the limited NOx reduction that was being obtained at the 25,000 mile test point.

Here too, adequate vehicle maintenance and periodic emission control system inspection were shown to be necessary to ensure continued satisfactory emission reductions using this device.

3.3 FLEET TEST OF GENERAL MOTORS RETROFIT SYSTEM

3.3.1 BACKGROUND

Previous tests by the Environmental Protection Agency using a small number of pre-controlled automobiles had indicated that a retrofit system developed by the General Motors Corporation appeared capable of achieving significant reductions in emissions of all three major automotive pollutants (HC, CO, and NOx) at a relatively low cost. Similar systems have been developed by other U.S. automobile manufacturers. As a result, a program to obtain more extensive fleet test data for this type of system evaluated using the Federal emission test procedure was initiated. The General Motors system was selected for testing because of its general applicability to domestically manufactured cars, and because of the previous test experience with it. This evaluation was conducted roughly in parallel with the survey of retrofit emission control technology discussed in Section 3.2.

DESCRIPTION OF SYSTEM

This retrofit system consists principally of an exhaust emissions-oriented engine adjustment procedure. The control specifies the use of increased idle speed, leaner idle mixture and retarded ignition timing. A thermostatic vacuum switch provides engine overheating protection by restoring the normal ignition timing if high cooling system temperatures occur.

Installation of the system requires a competent mechnaic. Idle air-fuel mixture is set at the ratio of 14 to 1. This can be accomplished accurately using a combustion analyzer available in many shops, or approximated by using an engine speed drop-off method detailed in the device installation instructions. Idle speed is increased to 600 rpm to smooth the leaner engine operation. Normal manufacturer's recommended ignition timing is specified and the vacuum timing advance is made inoperative during normal operation. Through use of a thermostatic vacuum switch, vacuum advance is restored if the engine collant temperature exceeds 205 F.

SYSTEM APPLICABILITY

The simplicity of the design of this retrofit approach enables almost universal application to domestically manufactured pre-controlled vehicles from 1955 through 1967 or to vehicles manufactured for sale in California through 1965. The system is not applicable to the segment of this population which utilized a distributor without centrifugal advance. Nor is the system generally available for imported passenger cars, although its principle of operation is applicable to many of these cars. The manufacturer does not recommend application of the device to controlled vehicles.

3.3.2 DESCRIPTION OF TEST PROGRAM

A test program was designed to establish the emission control effectiveness of this retrofit system. It was also desirable in conjunction with this evaluation to obtain data on the control potential of standard tune-up procedures, lean tune procedures, and combinations of these procedures with the retrofit system. Both tune-up procedures specified the replacement of spark plugs, spark plug wires, distributor rotor, distributor cap, ignition points, condenser and air filter element. The procedures differed in the fact that the lean tune-up set idle air-fuel mixture at a 14 to 1 level, while the normal tune-up called for a mixture setting to give best minifold vacuum at idle, effectively a richer fuel mixture. All other tune-up settings were as specified by the vehicle manufacturers.

A fleet of 110 automobiles statistically typical of the nationwide population of pre-emission controlled domestic vehicles was used for the testing. The sample was limited to model years 1962-1967 inclusive. The selection of models was based on model sales figures and included vehicles with automatic and standard transmissions. Optional engines for the highest sales volume models were included. Because of the location of the study, (Los Angeles) the cars typified maintenance states found in the southwest United States. The vehicles were obtained through a contractor from private individuals to assure a sample of typically operated and maintained cars. No rental fleets, used car lots, or similar sources were employed. Cars were rejected from the program that suffered from obvious gross mechanical defects which would jeopardize their probability of completing the test sequence, thus resulting in a sample somewhat biased toward better-maintained vehicles. As required in the emission testing procedures, the vehicles were checked for leak-free exhaust systems.

All emission tests were conducted according to the 1972 Federal Test Procedure.[3] The instrumentation employed for the analysis of bag samples for HC and CO was identical to that specified for certification testing; Saltzman analysis was used to determine oxides on nitrogen on all tests.

Each vehicle received in the laboratory was subjected to a four phase test sequence. Initially, "baseline" or "as received" emissions were determined. This test was followed by installation and adjustment of the retrofit system and subsequent emission testing. The vehicle was then "tuned," the retrofit device detached, and another test was performed. Finally the retrofit was reactivated and the vehicle was tested in the combination configuration of "tuned and retrofit."

Fuel consumption over the LA4 driving cycle was measured during each test to evaluate inherent benefits or penalties for each control technique. On the first 25 vehicles driveability effects were qualitatively evaluated by a short road test following each dynamometer test Engine overheating tendencies were monitored during the emission tests on all cars.

3.3.3 RESULTS OF EVALUATION

EMISSION REDUCTION EFFECTIVENESS

Table 3-4 indicates the relative effectiveness of the various configurations compared to the emissions from the "as received" or "baseline" vehicle. The "tuned with retrofit" configuration showed overall the greatest control potential, with "retrofit alone" having somewhat lower effectiveness. Statistically, the hydrocarbon and carbon monoxide levels of these two configurations are significantly different. The oxides of nitrogen reductions measured are not statistically different for the two configurations. The emission control achieved by "normal tune-up" is presented in Table 3-4. The "lean tune-up" is not included because the quantity of test data was inadequate to predict control effectiveness with a reasonable level of confidence.

The discussion above relates to the effectiveness of the retrofit system alone, and in combination with tune-up, in reducing the emissions of pre-controlled vehicles in typical states of owner maintenance. The reductions cited would be the appropriate ones to consider in evaluating the initial effectiveness of a retrofit program not combined with any mandatory maintenance or inspection/maintenance program. It is also important to consider the additional effectiveness which would be gained by applying this retrofit system to pre-controlled vehicles already in a tuned-up condition. This represents the additional effectiveness of adding a retrofit program to a mandatory maintenance or inspection/maintenance program. The results of this analysis are presented in Table 3-5.

Table 3-4

Emission Reduction Data % Reduction from "as Received" Baseline

Configuration	Retrofit Alone	Normal Tune	Tuned with Retrofit
Number of vehicles in test sample	110	85	110
Effectiveness			
HC-Mean	26%	15%	34%
95% Confidence	24% to 29%	11% to 18%	33% to 38%
CO-Mean	16%	11%	18%
95% Confidence	14% to 17%	9% to 13%	17% to 20%
NO-Mean	22%	-4% inc.	20%
95% Confidence	15% to 30%	-18% to 10%	13% to 27%

Table 3-5

Emission Reduction Data of Tune-up vs. Tune-up and Retrofit Combined % Reduction from Tuned Baseline

Configuration	Normal Tune and Retrofit
Number of vehicles in test sample	85
Effectiveness (% Reduction from Tuned Baseline)	
HC-Mean	25%
95% Confidence	22% to 28%
CO-Mean	9%
95% Confidence	6% to 11%
NOx-Mean	23%
95% Confidence	15% to 29%

When applied to tuned-up vehicles, the addition of the retrofit system resulted in significant reductions in hydrocarbon, carbon monoxide, and oxides of nitrogen levels.

RELIABILITY OF SYSTEM

An investigation into the durability of the system was conducted by General Motors as part of their development effort.[4] A fleet of eight vehicles was run 25,000 miles with the retrofit system installed. Mileage was accumulated according to the AMA durability schedule for emission data. Deterioration factors developed for this fleet were as follows:

General Motors Retrofit System

Deterioration Factors[4]

HC	1.01
CO	1.20
NOx	1.00

These data reflect deterioration factors of the retrofit system alone. Normal vehicle deterioration has been analytically removed. These factors were developed from tests using the 1968 7-mode test procedure and may be somewhat different than if they had been determined using the 1972 Federal test procedure. It should be kept in mind that these are probably minimum values as the mileage was accumulated over a very short time rather than in typical customer usage. The rather large factor for carbon monoxide means essentially that after 25,000 miles of operation, the retrofit system's effect on that pollutant was negligible. Thus, a need for periodic readjustment of the carburetor is indicated.

The hardware used in conjunction with the system includes simple standard automotive parts, and reliability of those components is not anticipated to present a problem.

It should be kept in mind that the retrofit system does not aleviate mechnical and electrical malfuctions that exist prior to installation. Nor will it protect the engine from normal degradation problems associated with automobiles. Thus, to ensure continued low emission levels for a particular vehicle with the system installed, it would be necessary to follow a normal vehicle maintenance schedule.

COST

While the magnitude of the emission reductions for this retrofit system is not exceedingly high, the installed cost of the system is low. The system retails at a cost of less than $10. Labor cost for installation would be about $10. Thus the total initial cost to the consumer would be less than $20.

Maintenance specifically related to the system itself would be limited to a carburetor adjustment at a cost of about $5 per year. A fuel consumption penalty of about 1% to 2% was associated with the retrofit system. This would represent an additional cost to the average consumer of about $3.00 per year.

SAFETY AND DRIVEABILITY EFFECTS

This retrofit system has no known adverse safety effects associated with its installation. Potential engine overheating tendencies associated with the vacuum advance disconnect are well guarded against through the use of the thermostatic vacuum switch.

Engine overheating as a result of very heavy traffic conditions could temporarily restore vacuum advance on a portion of the retrofitted vehicles. This could result in decreased emission control effectiveness (principally for oxides of nitrogen and hydrocarbons) under such driving conditions. No data are available to indicate whether this effect occurs in actual use.

The Environmental Protection Agency performed limited driveability evaluations with the retrofit installed. The results of these tests tended to confirm results previously reported by the device developer.[4] The device developer reported that cold start and driveaway ratings of ten vehicles tested showed no real difference between "as received" and "kit installed" configurations. Warm driveability ratings on 91 vehicles gave mixed results. Of the 91 vehicles, 20 cars demonstrated worse driveability with the device, 14 were improved, and no effect on the remaining 57 was noted. Of the 20 vehicles whose driveability deteriorated, most of the problems were associated with a "stretchy" feel when the throttle was depressed at light loads.

Thus, it appears that neither safety nor driveability effects result in serious reservations as to the feasibility of this retrofit system.

3.4 COST AND EFFECTIVENESS OF RETROFIT STRATEGIES

3.4.1 INTRODUCTION

Sections 3.2 and 3.3 have presented data on the per vehicle emission reductions and costs associated with applying various retrofit approaches to pre-controlled light duty vehicles. To the air pollution control official, however, the subject of principal interest is the overall effectiveness of retrofit programs in reducing vehicular emissions. The per vehicle emission reductions and costs are basic data necessary for evaluation of the effectiveness and cost of programs using such approaches; and, except for possible effects of altitude on the levels of emission reductions which are achievable, are generally applicable throughout the nation. Overall program effectiveness and cost, on the other hand, depend upon a number of region-specific factors such as the relative numbers and annual mileages of vehicles of various model years. In addition, the relative values of various retrofit or other in-use vehicle emission control programs will depend upon the nature and magnitude of the air pollution problems to be solved and the time period over which in-use vehicle emission reductions are required. The result is that decisions on the relative merits of various in-use vehicle emission control programs must generally be made after the alternatives have been analyzed for the specific region under consideration. However, to illustrate some of the considerations involved, and to provide a perspective on the overall costs and effectiveness of retrofit programs, this section presents the results of some typical calculations of overall retrofit program cost and effectiveness based upon nationwide average vehicle population data.

3.4.2 EVALUATION OF OVERALL EFFECTIVENESS AND COST OF RETROFIT STRATEGIES

The principal factors which influence the overall cost and emission reduction effectiveness of a retrofit program are:

- Time period required to implement the retrofit program.
- Number of vehicles which will be retrofitted under the program.
- Fraction of total vehicular emissions contributed by the vehicles to be retrofitted.
- Per vehicle emission reductions achievable with the retrofit approach under consideration.
- Need for periodic inspection and maintenance of retrofitted vehicles.
- Extent and rate of deterioration of retrofit emission control performance over time.
- Per vehicle costs assocated with the retrofit approach under consideration.
- Administrative costs associated with the implementation and operation of the retrofit program.
- Costs associated with any inspection/maintenance program necessary for the retrofitted vehicles.
- Rate of retirement of the retrofitted vehicles from the vehicle population.

As older vehicles which are potentially subject to retrofit approaches are replaced by newer vehicles with lower initial emission levels, the potential effectiveness of a retrofit strategy will decrease substantially. Thus, the time period over which emission reductions are required plays a key role in determining the usefulness of a retrofit strategy.

To evaluate the overall effectiveness and cost of retrofit strategies, the factors mentioned above must be quantified using data specific to the region for which retrofit is being considered. The key factors which vary from one region to another are the number of vehicles to be retrofitted, the fraction of total vehicular emissions emitted by those vehicles as a function of time, and the rate of retirement of retrofitted vehicles from the vehicle population; these factors are determined by the composition of the vehicle population in the region.

3.4.3 COMPARISON OF EFFECTIVENESS AND COST OF SELECTED RETROFIT STRATEGIES

As noted earlier in this section, the calculation and comparison of figures for the overall emission reduction effectiveness and cost of retrofit strategies requires the use of data which can vary substantially from one air quality control region to another. Presented below are the results of calculations of overall effectiveness and cost for some retrofit strategies which have been based on typical data. These calculations illustrate the magnitudes of the emission reductions achievable by certain retrofit approaches, but the results cannot be applied directly to the needs of any specific air quality control region without a determination that the data used are representative of the region under consideration. It should also be noted that the calculations presented below are for single retrofit strategies only; no attempt has been made to identify an optimum retrofit strategy which might combine the use of various retrofit approaches on different segments of the in-use vehicle population.

For the purpose of these calculations, it has been assumed that each of the retrofit programs, and any adjunct inspection/maintenance program, would be implemented by January 1, 1975. Vehicle population data used have been nationwide average values; and an annual linear growth rate of total vehicle miles travelled has been assumed at five percent. In strategies employing exhaust emission retrofit, it has been assumed that the retrofitted vehicles will be subjected to an annual inspection/maintenance program, since the results presented in section 3.2 and 3.3 indicate that continued effectiveness of exhaust emission retrofit devices can be assured only by periodic inspection/maintenance of all exhaust emission related systems on retrofitted vehicles, including those not specifically included in the retrofit. The following types of retrofit strategies have been considered:

CRANKCASE EMISSION RETROFIT

Crankcase emission retrofit of all pre-1968 model year light duty vehicles.

EVAPORATIVE EMISSION RETROFIT

1. Evaporative emission retrofit of all pre-1971 model year light duty vehicles.
2. Evaporative emission retrofit of all 1968 through 1970 model year light duty vehicles.

EXHAUST EMISSION RETROFIT - PRE-CONTROLLED VEHICLES

1. Exhaust emission retrofit of all pre-1968 model year light duty vehicles with a maximally effective device and inspection/maintenance of all retrofitted vehicles.

2. Exhaust emission retrofit of all pre-1968 model year light duty vehicles with a device which is maximally effective for a specific pollutant (CO was taken for this example) and inspection/maintenance of all retrofitted vehicles.

3. Exhaust emission retrofit of all pre-1968 model year light duty vehicles with a retrofit device which accomplishes smaller than maximum reductions of all major automotive pollutants, but a relatively low cost, and inspection/maintenance of retrofitted vehicles.

EXHAUST EMISSION RETROFIT - CONTROLLED VEHICLES

1. Exhaust emission retrofit of all 1968 through 1972 model year light duty vehicles with maximally effective devices and inspection/maintenance of all retrofitted vehicles.

2. Exhaust emission retrofit of all 1973 and 1974 model year light duty vehicles with maximally effective devices and inspection/maintenance of all retrofitted vehicles.

Table 3-6 presents the emission reductions and costs per vehicle used for these calculations. Emission reductions for exhaust emission retrofit approaches are presented as reductions relative to a tuned vehicle baseline since inspection/maintenance of retrofitted vehicles is assumed. It is assumed that with annual inspection/maintenance of all retrofitted vehicles the reductions cited in Table 3-6 will be maintained without deterioration. Cost data are stated as the present cost in 1972 dollars. In the calculations of overall program cost, corrections are made for inflation at a five percent annual rate and the future costs are discounted to present worth using and eight percent discount rate.

Emission reductions for crankcase and evaporative emission retrofit systems are based on the effectiveness of systems now being installed on new vehicles. Costs for those systems are based on estimates made in EPA's survey of retrofit emission control methods.[2] Emission reduction and cost data for pre-controlled vehicle exhaust retrofit approaches are based upon the data presented in sections 3.2 and 3.3. Data for controlled vehicle exhaust retrofit are extrapolated from the available data for pre-controlled vehicles. It has been assumed that an oxidizing catalytic reactor capable of 50% reductions in both HC and CO can be applied to all 1968 through 1974 model light duty vehicles and that an exhaust gas recirculation system capable of achieving a 40% reductoion in NOx could be applied to 1968 through 1972 models. Cost data for controlled vehicle retrofit are based on those for pre-controlled vehicles. Emission reduction and cost data for inspection/maintenance are discussed in Chapter 2 of this document.

TABLE 3-6

TYPICAL EMISSION REDUCTIONS AND COSTS PER VEHICLE

Approach	Emission Reductions per Vehicle* Crankcase HC	Evaporative HC	Exhaust HC	Exhaust CO	Exhaust NOx	Cost per Vehicle** Initial Installed Cost	Incremental Operating Cost
Crankcase Retrofit	100%	0%	0%	0%	0%	$40	$0.25/1,000 mi.
Evaporative Retrofit	0%	95%	0%	0%	0%	$140	$.35/1,000 mi.
Maximally Effective Exhaust Retrofit for Pre-Controlled LDV	0%	0%	70%	65%	50%	$160	$1.00/1,000 mi.
CO Specific Exhaust Retrofit for Pre-Controlled LDV	0%	0%	20%	60%	0%	$60	$0.50/1,000 mi.
Low Cost Exhaust Retrofit for Pre-Controlled LDV	0%	0%	25%	10%	25%	$20	$0.00/1,000 mi.
Maximally Effective Exhaust Retrofit for 1968 thru 1972 LDV	0%	0%	50%	50%	40%	$200	$2.00/1,000 mi.
Maximally Effective Exhaust Retrofit for 1973 and 1974 LDV	0%	0%	50%	50%	0%	$160	$1.00/1,000 mi.
Inspection/Maintenance	0%	0%	12%	10%	0%	NA	$4.00/ year

* Exhaust emission reductions are relative to a tuned baseline
** Cost expressed as present cost in 1972 dollars

Table 3-7 presents a comparison of the overall costs and effectiveness of the various retrofit strategies considered. The cost figures are total cost for each retrofit strategy over the time period 1975 through 1979 expressed in 1972 dollars, annualized, and distributed over the entire 1975 light duty vehicle population. Included are the costs for: purchase and installation of retrofit devices; regular maintenance of the retrofit systems; annual emission inspection of the retrofitted vehicles and; maintenance required by the inspection/maintenance program beyond that normally performed voluntarily. Administrative costs for implementing the retrofit programs have not been specifically included but, in the case of the exhaust emission retrofit strategies, these costs are probably covered by the costs for administration of the inspection/maintenance program included in the assumed inspection cost. Fuel consumption savings or penalties resulting from the programs have not been included because of uncertainty in such figures.

Emission reduction effectiveness of each of the strategies is presented for 1975, 1977 and 1980 as the projected light duty vehicle emissions in those years if the strategy were implemented, normalized with respect to light duty vehicle emissions in 1967. For comparsion, the projected emissions without any in-use vehicle control program are also presented for each year.

The results presented in Table 3-7 lead to the following conclusions:

* The costs and emission reduction effectiveness of various retrofit strategies vary substantially. The choice of a "best" retrofit approach must be tailored to the specific pollutants whose emissions must be reduced, the magnitude of the reductions required, and the time period over which the reductions are needed.

* Programs for retrofitting pre-controlled light duty vehicles could have a significant influence on light duty vehicle emissions in 1975 and 1977 but would generally have only minimal effects in 1980 and beyond.

* Programs for retrofitting more effective exhaust emission controls to pre-1975 model year controlled light duty vehicles could significantly decrease light duty vehicle emissions even beyond 1980.

* Retrofitting of crankcase emission control systems to vehicles not originally equipped with such devices would have a minimal effect on light duty vehicle emissions in the 1975 to 1980 time period.

* Retrofitting evaporative emission control systems to light duty vehicles not originally so equipped could bring about some decrease in HC emissions during the 1975 to 1980 time period but does not appear cost-effective relative to retrofitting exhaust emission controls to the same vehicles.

Once again, it must be emphasized that these conclusions are for a light duty vehicle population similar in age and mileage distribution to the nationwide average. Markedly different age and mileage distributions could alter these results.

TABLE 3-7

COMPARISON OF OVERALL EFFECTIVENESS AND COSTS OF VARIOUS RETROFIT STRATEGIES*

Retrofit Strategy	1975-1980 Annualized Cost per Vehicle**	Light Duty Vehicle Emissions Relative to 1967 Base								
		1975			1977			1980		
		HC	CO	NOx	HC	CO	NOx	HC	CO	NOx
No in-use vehicle emission control program	$0	0.51	0.63	0.97	0.37	0.47	0.75	0.21	0.30	0.49
Crankcase emission retrofit of all pre-1968 model year light duty vehicles	$2	0.50	0.63	0.97	0.36	0.47	0.75	0.21	0.30	0.49
Evaporative emission retrofit of all pre-1971 model year light duty vehicles	$15	0.44	0.63	0.97	0.32	0.47	0.75	0.19	0.30	0.49
Evaporative emission retrofit of all 1968 through 1970 model year light duty vehicles	$8	0.47	0.63	0.97	0.34	0.47	0.75	0.20	0.30	0.49
Exhaust emission retrofit of all pre-1968 model year light duty vehicles with a maximally effective device for all pollutants and inspection/maintenance of retrofitted vehicles	$9	0.40	0.48	0.86	0.30	0.39	0.69	0.20	0.28	0.48
Exhaust emission retrofit of all pre-1968 model year light duty vehicles with a device specifically effective for CO control and inspection/maintenance of retrofitted vehicles	$4	0.47	0.49	0.97	0.34	0.40	0.75	0.21	0.28	0.49
Exhaust emission retrofit of all pre-1968 model year light duty vehicles with a low cost device partially controlling all pollutants and inspection/maintenance of retrofitted vehicles	$1.50	0.46	0.59	0.92	0.34	0.45	0.72	0.21	0.29	0.48
Exhaust emission retrofit of all 1968 through 1972 model year light duty vehicles with maximally effective devices and inspection/maintenance of retrofitted vehicles	$26	0.38	0.44	0.77	0.26	0.32	0.60	0.17	0.22	0.40
Exhaust emission retrofit of all 1973 and 1974 model year light duty vehicles with maximally effective devices and inspection/maintenance of retrofitted vehicles	$8.50	0.42	0.50	0.97	0.28	0.34	0.75	0.16	0.21	0.49

* Calculated using nationwide average vehicle population data - results for specific air quality control regions would differ.
** Total cost for 1975 through 1979 time period in 1972 dollars annualized and distributed over entire 1975 light duty vehicle population.

3.5 CONCLUSIONS

Retrofit Device Feasibility

Several exhaust emission control approaches appear feasible for retrofit to pre-1968 (pre-1966 in California) model year light duty vehicles. These approaches include air bleed to intake manifold, catalytic converter with vacuum spark advance disconnect, exhaust gas recirculation with vacuum spark advance disconnect, and lean idle adjustment with vacuum spark advance disconnect. Other exhaust emission control retrofit approaches may also be applicable to pre-controlled vehicles but have not been tested as extensively as the above.

Retrofit application of some of the above approaches to controlled (post-1967 models nationwide, post 1965 in California) light duty vehicles may also be feasible but empirical test data are very limited. Based upon emission control systems being developed for new vehicles, catalytic converter and exhaust gas recirculation approaches appear likely to be applicable to controlled vehicles. As retrofits, the catalytic converter would be potentially applicable to light duty vehicles through the 1974 model year and exhaust gas recirculation potentially applicable through the 1972 model year (except for a limited number of earlier models already employing this technique). Other retrofit approaches may also be applicable to controlled vehicles but cannot be considered feasible without further evaluation.

Exhaust emission control retrofit programs should not be implemented for either pre-controlled or controlled light duty vehicles except in conjunction with an inspection/maintenance program which will assure continued satisfactory operation of emission-related systems or the retrofitted vehicles.

Retrofit of crankcase emission control systems to light duty vehicles not already equipped with such systems is considered feasible. Retrofit of evaporative emission control to light duty vehicles not equipped with such control systems is potentially feasible but no evaporative emission control retrofit systems are currently available.

Retrofit Device Effectiveness and Cost

Retrofit exhaust emission control systems appear capable of accomplishing reductions of up to 70% in HC emissions, 65% in CO emissions, and 50% in NO_x emissions from pre-controlled light duty vehicles. These maximum reductions can be achieved simultaneously through use of a catalytic converter with vacuum spark advance disconnect. Similar CO and NO_x reductions can be achieved separately by air bleed to intake manifold and exhaust gas recirculation with vacuum spark advance disconnect retrofits respectively. No other retrofit system (except gaseous fuel conversion) is known to rival the HC emission reductions achievable by the catalytic converter with vacuum spark advance disconnect.

Retrofit crankcase emission control systems could be expected to control essentially 100% of crankcase HC emissions. Based upon the effectiveness of evaporative emission control systems now being installed in new vehicles, retrofitting of similar systems to vehicles not originally equipped with evaporative emission controls could be expected to control approximately 95% of the evaporative HC emissions from those vehicles as measured by current test procedures.

Empirical test data on the effectiveness of retrofit approaches in reducing exhaust emissions from controlled light duty vehicles are very limited. However, based upon the effectiveness of those approaches for pre-controlled light duty vehicles and considering the nature of the emission control approaches already employed in controlled vehicles, reductions of approximately 50% in HC and CO from 1968 through 1974 model year light duty vehicles through retrofit of an oxidizing catalytic converter, and reductions of approximately 40% in NO_x from 1968 through 1972 model year light duty vehicles through retrofit of exhaust gas recirculation, appear possible.

Costs of retrofit emission control devices vary substantially, most falling within the range of $20 to $175 installed. In general, devices achieving larger reductions and capable of controlling larger numbers of pollutants effectively are among the more expensive. However, for pre-controlled vehicles devices are available which can achieve close to maximum reductions of either CO or NO_x singly at moderate or intermediate costs.

Retrofit Strategy Effectiveness and Cost

In general, the relative emission reduction effectiveness and costs of alternative retrofit strategies must be evaluated in terms of the specific region for which retrofit is being considered, since vehicle age and mileage distributions vary significantly throughout the nation. Using nationwide average vehicle population data as a typical case, it has been found that significant reductions in total light duty vehicle emissions can be achieved during the period 1975 to 1980 through retrofit of exhaust emission controls to pre-1968 model year light duty vehicles and even beyond 1980 if more effective exhaust emission controls are retrofitted to pre-1975 model year controlled light duty vehicles. Retrofit of crankcase emission controls to vehicles not so equipped appears to have a negligible effect beyond 1975.

Retrofit of evaporative emission controls to pre-1971 model year light duty vehicles could significantly reduce HC emissions during the 1975-1980 time period but appears substantially less cost-effective than exhaust emission retrofit.

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2. "Analysis of Effectiveness and Costs of Retrofit Emission Control Systems for Used Motor Vehicles," Final Report prepared under Environmental Protection Agency Contract No. 68-04-0038 by Olson Laboratories, Inc., in association with Northrop Corporation, May 1972.

3. Federal Register, Volume 35, Number 219, Part II, Tuesday, November 10, 1970, "Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines."

4. SAE Paper #710069, "Exhaust Emission Control for Used Cars," G.W. Niepoth, G.P. Ransom, J.H. Currie, International Automotive Engineering Congress, January 11-15, 1971.

Chapter 4 CONVERSION OF IN-USE VEHICLES FOR GASEOUS FUEL OPERATION

4.1 INTRODUCTION

The modification of in-use vehicles to permit their operation using gaseous fuels falls within the general definition of retrofit approaches discussed in Chapter 3 of this document. However, the feasibility of gaseous fuel conversion as a cost-effective in-use vehicle emission control strategy depends not only on the availability, emission reduction effectiveness, and cost of the retrofit hardware, but also on a number of other factors, such as the feasibility of providing the necessary fuel distribution system, the availability of adequate fuel supplies, and the impact of fuel diversion from other combustion sources. Therefore, the conversion of in-use vehicles for operation on gaseous fuels is dealt with separately in this chapter.

TYPES OF GASEOUS FUEL CONVERSIONS

There are three basic types of gaseous fuel conversions that may be performed which differ according to fuel type. These are: Liquified Petroleum Gas (LPG), Compressed Natural Gas (CNG), and Liquified Natural Gas (CNG). Differences among the types manifest themselves principally in such areas as the type of conversion hardware required, conversion cost, and operating convenience. In addition to these three basic types of conversions, a distinction can be made between single-fuel conversions, in which the vehicle is modified to operate exclusively on the gaseous fuel, and dual-fuel conversions in which the modified vehicle is equipped to operate interchangably on either the gaseous fuel or gasoline.

APPLICABILITY OF GASEOUS FUEL CONVERSION

Conversion for use of gaseous fuel can be performed for both light and heavy duty gasoline-powered vehicles. However, such conversions have generally been performed for reasons other than emission reduction (usually reduced operating or maintenance cost) and data evaluating the emission reduction capability of such conversions are available only for light duty vehicles. As a result, the emphasis in this chapter is placed on light duty vehicle conversions.

4.2 SUMMARY OF GASEOUS FUEL CONVERSION TECHNOLOGY

4.2.1 DESCRIPTION OF GASEOUS FUEL SYSTEMS

Conversion of a vehicle for operation on a gaseous fuel requires the installation of a new fuel tank designed to contain the fuel under pressure, the installation of new fuel lines and appropriate control valves to ensure that the fuel reaches the engine only when it is running, and the installation of a new carburetor designed to meter the flow of the gaseous fuel into the engine's induction system. Conversions for LPG and LNG also require the installation of liquid-gas converters which vaporize the fuel; and conversions for CNG and LNG require a series of pressure regulators to reduce the high pressure at the fuel tank to a pressure suitable for the carburertor. In single-fuel systems, the above components replace the original fuel tank, fuel lines, fuel pump, and carburetor. In dual-fuel systems, the new components must be added to the original components, since those are required when the vehicle is operated with gasoline fuel.

In addition to the new equipment which must be retrofitted to an in-use vehicle to permit it to use gaseous fuel, certain engine adjustments (such as ignition timing) may be required to achieve proper operation with the new fuel. Optimization of engine adjustments is necessary if maximum emission reductions are to be achieved. For vehicles not originally equipped with hardened valve seats, installation of such seats may be necessary to prevent excessive wear with certain types of vehicle useage.

A number of systems for conversion of light duty vehicles to gaseous fuel operation are currently available. It has been estimated[1] that several hundred thousand vehicles are currently being operated in the United States using LPG and that several thousand vehicles using natural gas, mostly CNG, are being operated experimentally.

4.2.2 EMISSION REDUCTIONS ATTAINABLE THROUGH GASEOUS FUEL CONVERSION

While a large number of vehicles have been converted for operation on gaseous fuels, evaluations of the emission reductions obtained through those conversions have been quite limited; particularly limited are test data using the 1972 or 1975 Federal certification test procedures.

Table 4-1 summarizes some of the available test results. It can be seen that substantial reductions in emissions of all three major automotive pollutants are achievable. For example, initial reductions of approximately 80% in exhaust HC and CO emissions and 60% in NOx emissions appear to be achievable concurrently when 1970 and earlier model year controlled light duty vehicles are converted for gaseous fuel operation and optimized with respect to ignition timing and air/fuel ratio. Alternatively, it can be stated that exhaust emission levels of approximately 0.6 grams per mile HC, 3 grams per mile CO, and 3 grams per mile NOx, as measured by the 1972 Federal test procedure, are achievable with existing gaseous fuel conversion systems. However, it must also be noted that in a number of cases either very small reductions or even large increases in emissions resulted when vehicles were converted for gaseous fuel operation.

TABLE 4-1

Typical Emission Reductions Through Gaseous Fuel Conversion

Vehicle	1972 FTP Emissions (grams per mile) HC**	CO	NOx	Type Conversion
Converted 1968 Buick 350	3.5	4.7	8.9	LPG
Stock 1968 Buick 350	1.9	29.6	4.0	
Percent Reduction	(84)*	84	(123)*	
Converted 1969 Ford 351	3.1	7.3	8.6	LPG dual fuel
Stock 1969 Ford 351	7.4	17.8	5.2	
Percent Reduction	58	59	(65)*	
Converted 1968 Ford 302	2.4	4.2	1.8	LPG dual fuel
Stock 1968 Ford 302	3.1	28.5	3.6	
Percent Reduction	23	85	50	
4 Converted 1969 Chrysler 318's	2.4	7.2	2.9	LPG dual fuel
Stock 1969 Chrysler 318	3.4	30.5	3.6	
Percent Reduction	29	76	19	
2 Converted Rambler 343's	3.0	15.4	2.6	LPG dual fuel
Stock 1969 Rambler 343	3.0	31.5	3.1	
Percent Reduction	0	51	16	
Converted 1969 Ford 429	1.3	4.0	1.9	LPG
10 Converted 1970 Ford 250's	0.69	1.8	2.6	LPG
10 Stock 1970 Ford 250's	3.70	16.0	9.4	
Percent Reduction	81	89	72	
10 Converted 1970 Rebel 232's	.51	3.9	3.1	LPG
10 Stock 1970 Rebel 232's	2.7	22.1	6.9	
Percent Reduction	81	82	55	

TABLE 4-1 (Cont.)

TYPICAL EMISSION REDUCTIONS THROUGH GASEOUS FUEL CONVERSIONS

Vehicle	1970 FTP Emissions (grams per mile) HC**	CO	NOx	Type Conversion
2 Converted 1968 Chevrolet 230's	1.1	9.5	---	CNG dual fuel
2 Stock 1968 Chevrolet 230's	3.7	58.2	---	
Percent Reduction	70	84		
2 Converted 1968 Ford 250's	0.9	7.8	---	CNG dual fuel
2 Stock 1969 Ford 250's	2.6	25.3	---	
Percent Reduction	65	69		
10 California State Cars	1.5	10.5	1.4	LPG
10 California State Cars	1.5	6.7	1.2	CNG dual fuel
Same Cars on Gasoline	3.1	42.9	3.2	
Percent Reduction	52	84	63	
5 Los Angeles City Cars	1.4	5.0	3.0	CNG dual fuel
Same Cars on Gasoline	2.9	31.0	3.5	
Percent Reduction	52	84	14	

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* Figures in parentheses () reflect increases in emissions.

** Although it is generally agreed that hydrocarbon emissions from gaseous fueled vehicles are less photochemically reactive than those from gasoline fueled vehicles, a Federal reactivity scale has not been defined which would allow quantitative correction for this factor. Therefore, all hydrocarbon values are reported on the same mass basis as gasoline.

In general, it is to be expected that dual-fuel conversions will not be capable of achieving as large emission reductions as are possible using single-fuel conversions, since compromises are required in various engine adjustments to permit interchangable operation using both the gaseous fuel and gasoline.

Data on the deterioration of emission performance of vehicles converted for gaseous fuel operation, as those vehicles accumulate time and mileage, are extremely limited. However, it appears reasonable to assume that reductions comparable to those cited above should be maintained if appropriate vehicle maintenance is practiced.

4.2.3 COSTS OF GASEOUS FUEL CONVERSION

Typical costs for gaseous fuel conversion hardware, excluding the costs of fuel tanks and labor for the conversions, have been estimated [1,2] to be approximately $300 for LPG and CNG and $350 for LNG. The cost of fuel tanks varies substantially with their size, which is determined by the desired operating range of the converted vehicle between fuelings. The same sources estimate fuel tank costs within the ranges $100 to $200 for LPG, $60 to $200 for CNG, and $400 or more for LNG, depending upon size. The same sources estimate installation labor requirements ranging from 4 hours to 12 hours, or approximately $50 to $150. Thus, minimum conversion costs per vehicle, including fuel tanks and labor, can be estimated at approximately $450 for LPG, $410 for CNG, and $800 for LNG.

In addition to the cost of conversion hardware, several other factors may play an important role in determining the cost of a gaseous fuel conversion strategy. These are cost of refueling facilities, fuel cost, and maintenance costs. The cost of refueling facilities depends upon the gaseous fuel used; the number of vehicles to be serviced by the facility, and the fueling speed which is desired. Fuel costs vary substantially throughout the country and must be assessed for the specific area in which gaseous fuel conversion is contemplated. While experience with gaseous fuel conversions generally shows a reduction in vehicle maintenance costs for such items as oil and filter changes and spark plug replacement, available data on the savings in maintenance costs achieved by gaseous fuel conversion vary widely.[2,3]

4.2.4 OTHER ASPECTS OF GASEOUS FUEL CONVERSION

Other factors which influence the feasibility of gaseous fuel conversion approaches are effects on vehicle performance and safety considerations. In general, experience with gaseous fuel conversion fleets has demonstrated that acceptable vehicle performance (though often reduced from that obtained with gasoline) can be obtained with gaseous fuels. While safely considerations have restricted the use of gaseous fuels in some areas, enough experience has been accumulated with gaseous fuel vehicles to demonstrate that under closely controlled fleet operation the fuels can be used safely. Both of these aspects of gaseous fuel conversion are discussed in other documents.[1,3,4]

4.3 USEFULNESS OF GASEOUS FUEL CONVERSION AS AN IN-USE VEHICLE EMISSION CONTROL STRATEGY

In judging the usefulness of gaseous fuel conversion as an emission control strategy for in-use vehicles, the following factors must be considered: reductions in total vehicle population emissions achieveable as a function of time by the conversion strategy; cost of implementing the strategy; and impact of the diversion of gaseous fuels for vehicle use on other fuel requirements, including possible increases in emissions from stationary sources through fuel switching.

Considerations of the cost of gaseous fuel conversions, the limited availability and cost of refueling facilities, and limitations on the availability of gaseous fuels in many areas have generally led investigators to the conclusion that gaseous fuel conversion is most practical when applied to controlled fleets of vehicles.[3,4] A recent paper[5] has estimated the overall effectiveness and cost of fleet conversion programs for two cases of some interest: taxicab fleets in New York City and in Washington, D.C. The results of that analysis indicate that emission reductions expected to result from converting the pre-1975 model year taxicab fleets in those two cities to gaseous fuels would be relatively small compared to the potential of other emission control strategies for in-use vehicles and would be very short lived.

In another analysis[1,4], the overall emissions impact of diverting natural gas from electric power generation to powering commercial vehicles in New York City has been considered. It was determined that to operate all commerical vehicles in New York City on natural gas would require the diversion of approximately one-half of the quantity of that fuel currently used for electric power generation. Based upon emission rates typical of the 1968 to 1970 time period, and assuming that the natural gas diverted from power generation would be replaced by 1% sulfur fuel oil, it was estimated that such a control strategy could result in net reductions in HC and CO emissions equivalent to approximately 15% to 25% of the emissions of those pollutants from all motor vehicles in New York City. However, it was also found that a concurrent increase of emissions of sulfur oxides equivalent to approximately 6% of the total New York City emissions of that pollutant would result from implementing such a control strategy. This is an example of the type of pollutant control trade-offs which need to be evaluated in regions where supplies of gaseous fuels are limited.

4.4 CONCLUSIONS

The conversion of fleet-operated vehicles for operation using gaseous fuels is feasible with currently available technology. If properly optimized to minimize emissions, such conversions can achieve larger per-vehicle emission reductions than other, more generally applicable, retrofit approaches. The initial installed cost for gaseous fuel conversions is quite high relative to other retrofit approaches but in some cases this high initial cost can be substantially offset through savings in fuel and maintenance costs.

The usefulness of conversion of fleet vehicles for gaseous fuel operation as an in-use vehicle emission control strategy must be evaluated specifically for each region considering the approach since the fraction of the total vehicle population converted, fuel availability, fuel cost, and the impact of diversion of gaseous fuels from other air pollution sources will depend upon the region considered. However, the generally small portion of the total vehicle population which is fleet-operated, and the generally rapid replacement of fleet vehicles by newer models is likely to result in relatively small and short-lived emission reductions being achievable through this approach.

REFERENCES - CHAPTER 4

1. Emission Reduction Using Gaseous Fuels for Vehicular Propulsion, Institute of Gas Technology, Chicago, Illinois, June 1971 (Prepared under Contract No. 70-69 for the Environmental Protection Agency).

2. Analysis of Effectiveness and Costs of Retrofit Emission Control Systems for Used Motor Vehicles, Olson Laboratories, Inc., Anaheim, California, May 1972 (Prepared under Contract No. 68-04-0038 for the Environmental Protection Agency).

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4. Position Paper: Conversion of Motor Vehicles to Gaseous Fuel to Reduce Air Pollution, Office of Air Program, Environmental Protection Agency, May 1972.

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